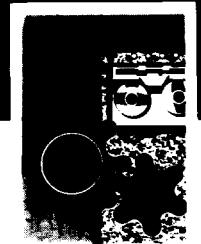


# **NIOSH**



A TECHNICAL REPORT

## **Estimates of Pulmonary and Gastrointestinal Deposition for Occupational Fiber Exposures**



ESTIMATES OF PULMONARY AND GASTROINTESTINAL  
DEPOSITION FOR OCCUPATIONAL FIBER EXPOSURES

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## ABSTRACT

A mathematical model for deposition of fibrous aerosols in the human respiratory tract was used to estimate pulmonary and gastrointestinal deposition fractions for 7 fiber types covering 19 industries or industrial operations. Fibers studied covered a wide range of airborne fiber diameters and lengths. The numerical fractions estimated to be deposited in the pulmonary spaces ranged from approximately 3 to 16% whereas the gastrointestinal fractions ranged from 11 to 59%. Large differences in deposition patterns for fibers in the size range considered most important for tumor production in laboratory animals by Stanton et al (1977) were also noted. Estimates of deposition mass fractions are presented and results of the study are discussed in light of available epidemiologic data on exposure to fibrous materials.

## ACKNOWLEDGEMENTS

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## INTRODUCTION

Naturally occurring fibrous materials have always been present in man's environment. There are hundreds of minerals which meet the definition generally used in occupational health to designate a fiber (i.e. a particle with an aspect ratio of 3 to 1 or larger); however, with the exception of the asbestos minerals, very few of these have been commercially exploited (Zumwalde and Dement, 1977). Many of these minerals may, however, occur as contaminants in other processed ores resulting in both occupational and environmental exposures. Man-made fibrous materials such as slag wool, rock wool and fibrous glass have been commercially produced only since approximately 1900. In fact, large scale fibrous glass production did not begin in the United States until the late 1930's (Smith, 1976).

Most epidemiologic studies of health effects relative to fiber exposures have been concerned with the asbestos minerals. The first report of death due to pulmonary fibrosis resulting from asbestos exposure was reported by Montague Murray in 1900; however, with the exception of other case reports, the first comprehensive study was by Merewether and Price in 1930. Not until 1935 was an association between asbestos and lung cancer reported by Lynch and Smith and not until 1960 was the association between mesothelioma and asbestos exposure made by Wagner. An excess risk of gastrointestinal cancer among working populations exposed to asbestos has been reported by numerous investigators and these studies have been reviewed by Schneiderman (1974). It is hypothesized that fibers initially deposited in the upper respiratory tract and subsequently swallowed are responsible for this excess cancer risk.

There are very little epidemiologic data relative to exposure to other types of fibrous materials. Several studies have been conducted among workers producing fibrous glass of relatively large fiber diameter (Wright, 1968; Utidjan, 1968; Nasr, 1971; Hill, 1973; Enterline and Henderson, 1975; Bayliss et al, 1976). These studies have not shown an excess cancer risk with such exposures; however, the study by Bayliss et al suggested a slight excess mortality risk for non-malignant respiratory disease excluding influenza. Preliminary results of an epidemiologic study of workers producing rock wool and slag wool suggest an increased risk of respiratory and gastrointestinal cancer with long latency periods (Ness et al, 1977); however, these conclusions must await further analysis.

Toxicological mechanisms for production of pulmonary fibrosis and respiratory cancer with exposure to asbestos are not well understood; however, a growing body of animal data suggest that these effects may be due to fiber dimensional considerations rather than physicochemical properties (Stanton et al, 1977). Numerous animal studies have shown that many types of fibrous materials may produce fibrosis and tumors upon injection or implantation (Stanton et al, 1977; Pott and Friedrichs, 1972; Pott et al, 1974; Wagner et al, 1976; Davis, 1976; Kuschner and Wright, 1976). The precise fiber dimensional characteristics required for these pathologic responses have been difficult to determine experimentally largely due to technical difficulties encountered in producing fibers

for study within narrow limits of diameter and length. It does appear that long, thin fibers may play an important role. Stanton et al (1977) concluded that fibers less than 1.5  $\mu\text{m}$  in diameter and longer than 8  $\mu\text{m}$  in length may be most important for production of pleural sarcomas upon implantation.

Even with more precise delineation of fiber size characteristics necessary for tissue damage and tumor production, extrapolation of animal data, generated by implantation or injection of fibers, to man should be done with caution. The ability of fibers with appropriate dimensional characteristics to reach critical sites such as the pulmonary spaces or the gastrointestinal tract must be considered. In addition, respiratory clearance for different fiber types may be very important. For example, several investigators have found glass fibers to be cleared more rapidly than asbestos (Kuschner and Wright, 1976). Differences in fiber clearance may be related to reactions with lung macrophages and to cytotoxicity of the material in question (Davis, 1976).

In any event, it is clear that fiber deposition may be an important factor to be considered in evaluating health risks associated with exposures to fibrous materials. The major objective of the current study was to estimate the fraction of airborne fibers of various types and in various industrial settings predicted to be deposited in the deep pulmonary spaces and that fraction which may be ingested. Deposition estimates were also generated for those fibers considered most significant by Stanton et al (1977) for tumor production. For purposes of this study "significant fibers" were considered to be those less than 1.5  $\mu\text{m}$  in diameter and longer than 5  $\mu\text{m}$  in length.

## METHODS

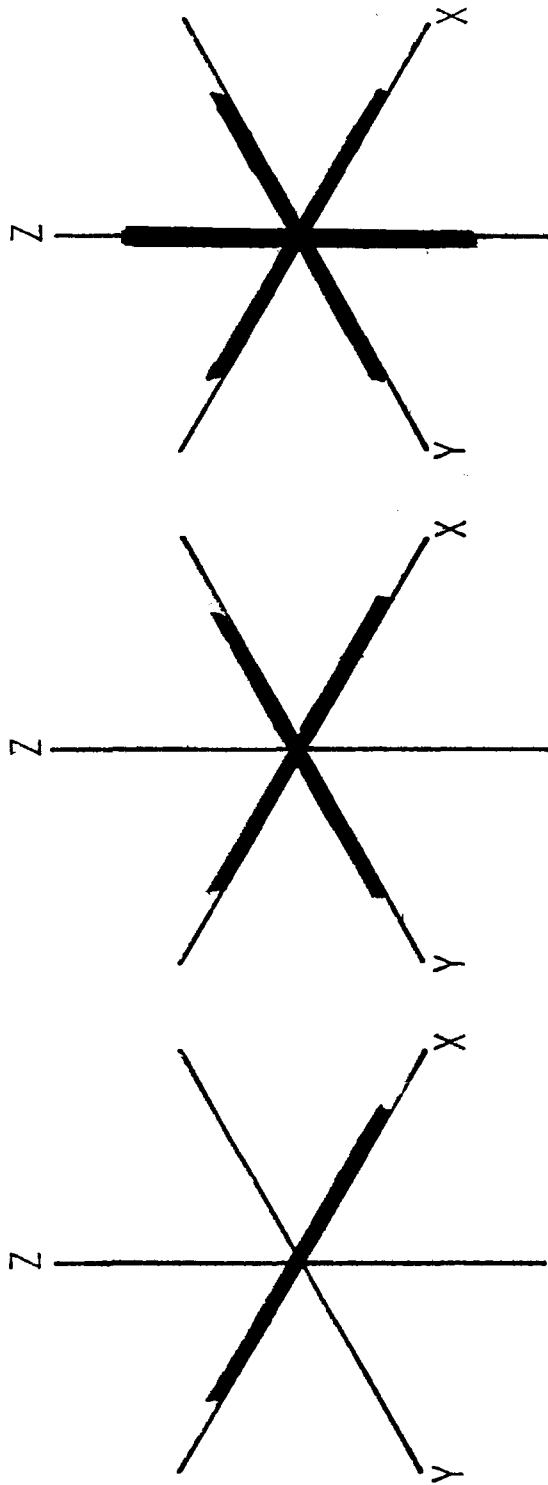
### DEPOSITION MODEL

Mathematical models have been offered to describe deposition in the human respiratory system of compact particles (Findeisen, 1935; Task Group on Lung Dynamics, 1966). The aerodynamic behavior of elongated particles and fibers, and the characteristics which influence their deposition, however, differ from those of compact particles. Factors influencing the deposition of fibers in the respiratory system have been described (Timbrell, 1965) and a mathematical model for predicting the deposition of uniform straight rods of high aspect ratio (length/width) has been developed (Harris and Fraser, 1976). This model is based upon a regular dichotomous configuration (Weibel, 1963) of the respiratory system, the mechanics of airflow within the system, and the aerodynamic behavior of cylindrical rods. The model developed by Harris and Fraser was used for this study. Mathematical expressions for fiber deposition probabilities according to deposition mechanism for the model may be found in Appendix A. The model incorporates the predictable periodic motion of rods of high aspect ratio in viscous flow (Goldsmith and Mason, 1962) which shows that fibers will have their major axes closely aligned with streamlines of the fluid most of the time. Those "ordered fibers" thereby present a smaller interception cross-section than would be the case if they were randomly oriented.

Many fibers encountered in the occupational environment are not uniform straight rods and this must be considered in deposition predictions. The model for straight rods in periodic motion (ordered rods) has been modified for a "worst case" assumption of random orientation in airways for single rods and simple aggregations (Harris and Timbrell, 1977). Three rod configurations were chosen for random orientation deposition estimates: (1) single rods, (2) two rods which lie in the same plane and whose ends may be bounded by a circumscribing circle (double rods) and (3) three rods, each normal to the others, whose ends may be bounded by a circumscribing sphere (triple rods). These configurations are depicted in Figure 1.

For the present study, the pulmonary deposited fraction is considered to be those fibers deposited beyond the ciliated portion of the respiratory system. The ingested or gastrointestinal fraction are those fibers cleared by the nasopharynx and tracheobronchial clearance processes and swallowed and is approximated on the assumption that all fibers deposited in the tracheobronchial compartment and three-fourths of those deposited in the nasopharynx beyond the nasal hairs are cleared to the gastrointestinal tract. Estimates of the fractions of rods of various lengths, aerodynamic equivalent diameters and fiber configurations predicted to be deposited in each respiratory compartment, to be exhaled and to be ingested are given in Appendix B. A tidal volume of 1450 cm<sup>3</sup> is assumed. The Task Group on Lung Dynamics (1966) respiratory cycle is used in the deposition model; however, the cycle has been altered to show a pause of 0.20 seconds exhalations and no pause after inhalation. This cycle consists of an inspiration of 1.74 seconds and expiration of 2.06 seconds (Harris and Fraser, 1976).

Figure 1  
 Fiber Configurations for Random  
 Orientation in Models.



ORDERED - O  
 SINGLE - S

DOUBLE - D

TRIPLE - T

It is emphasized that the above deposition model is not validated and the deposition values presented in this report are not offered as absolutely quantitative. It is suggested, however, that these estimates may represent qualitative differences in pulmonary space deposition or ingestion of inhaled fibrous aerosols having markedly different size and/or length distributions.

#### AIRBORNE SAMPLES AND SIZE DETERMINATIONS

The airborne fiber samples used for this study were collected by NIOSH during numerous field investigations between approximately 1971 and 1977. All were personnel, breathing zone samples collected for determinations of 8 hour, time-weighted-average fiber exposures in the particular industry and operation being studied. Samples were collected on Millipore Type AA membrane filters (37 mm diameter) at flow rates ranging from 1.7 to 2.0 liters per minute. Sampling periods ranged from 30 minutes to 5 hours depending on relative dust levels.

Airborne samples were analyzed in several ways. Counts of fibers longer than 5  $\mu\text{m}$  were performed on each sample using the phase contrast, optical microscopic method recommended for asbestos fibers (NIOSH, 1972). Fibers of each material were defined to be those particles with an aspect ratio (length/width) of 3-to-1 or greater. These data were used to calculate concentrations of airborne fibers with lengths longer than 5  $\mu\text{m}$ .

In addition to fiber concentration determinations, samples were also analyzed to determine lengths and diameters of airborne fibers. For these analyses, both optical and electron microscopy were employed depending on the size of the fibers being studied. A summary of the methods used, number of samples analyzed for size distribution and number of fibers sized for each fiber type and industry is given in Table 1. For all fiber types except mineral wool, transmission electron microscopy was the principle method used with magnifications ranging from 10,000 to 17,000 X. The large fiber sizes for the mineral wool samples made analysis by phase contrast optical microscopy the most practical method. Electron microscopic analyses of randomly selected mineral wool samples revealed no fibers less than 0.5  $\mu\text{m}$  in diameter which might be missed by phase contrast microscopy. For fibrous glass samples involving small diameters or so called "microfibers", both optical and electron microscopy were used with fibers < 0.5  $\mu\text{m}$  in diameter sized by electron microscopy and fibers >0.5  $\mu\text{m}$  in diameter sized by phase contrast optical microscopy using oil immersion objects at a magnification of approximately 970X. This approach was necessary due to the small diameter and long lengths of these fibers.

Samples analyzed by optical microscopy were prepared by the direct filter clearing method recommended for asbestos fiber counting (NIOSH, 1972). Samples analyzed by electron microscopy were prepared by the direct mounting method described by Zumwalde and Dement (1977). This method retains the original fiber size distribution with little loss of collected material.

Both fiber diameter and length were simultaneously determined for each fiber sized. Fiber diameter was defined to be the maximum transverse dimension of the particle while length was defined to be the maximum chord of a circle

Table 1  
 Summary of Samples Analyzed and Analytical Methods Used  
 for Airborne Fiber Size Analyses

Fiber Type	Industry/Operation	Analysis Method	No. Samples Analyzed	No. Fibers Sized
Chrysotile	Textile/Fiber Preparation	EM	20	6,917
	Textile/Twisting	EM	20	5,817
	Textile/Weaving	EM	20	4,856
	Friction Products/Mixing	EM	22	6,143
	Friction Products/Forming	EM	18	3,767
	Friction Products/Finishing	EM	20	2,700
	Cement Pipe/Mixing	EM	20	2,345
	Cement Pipe/Forming	EM	20	2,555
	Cement Pipe/Finishing	EM	19	4,846
Amosite	Pipe Insulation/Mixing	EM	2	373
	Pipe Insulation/Forming	EM	2	277
	Pipe Insulation/Finishing	EM	2	229
Anthophyllite *	Talc/Mining and Milling	EM	27	849
	Talc/Mining and Milling	EM	10	319
Tremolite *	Talc/Mining and Milling	EM	27	241
Wollastonite	Wollastonite/Mining & Milling	EM	13	1,320
Mineral Wool	Acoustical Tile Manufacturing All Operations	PC	126	8,909
Fibrous Glass	Microfiber Production	EM&PCO	88	7,906
	Aircraft Insulation Fabrication	EM&PCO	41	2,498

EM - Electron Microscopy (10,000 to 17,000X)

PC - Phase Contrast Optical Microscopy ( 430X, dry objectives)

PCO - Phase Contrast Optical Microscopy ( 970X, oil immersion objectives)

\* - Fibers Identified by Analytical Electron Microscopy

containing the fiber. A "Porton" graticule was used for fiber size determinations with optical microscopy. For electron microscopic studies, fiber sizes were determined by comparison with calibrated circles or millimeter marks etched on the microscope viewing screen. Results of the airborne fiber size determinations for each fiber type, industry and operation studied are given in Appendix C. It should be pointed out that all fibers sized had an aspect ratio of at least 3 to 1 although comparison of size interval midpoints in some cells in Appendix C may give the impression that this was not the case.

#### PULMONARY AND GASTROINTESTINAL FIBER DEPOSITION ESTIMATES

Estimates of pulmonary and gastrointestinal fiber deposition for each fiber type, industry and operation were obtained by application of the deposition model predictions according to fiber length, aerodynamic equivalent diameter and fiber configuration (Appendix B) to the airborne fiber size data (Appendix C). A computer program was developed for these determinations. The basic steps in the program were as follows:

1. Aerodynamic equivalent diameters for fibers in each cell of the fiber diameter/length matrix (Appendix C) were determined. The midpoints of the size intervals were used for these determinations. The midpoint of the largest interval was approximated by extrapolation based on a log-normal size distribution.
2. The calculated aerodynamic equivalent diameter and fiber length for each fiber size matrix cell were compared with the model output given in Appendix B. Fractional pulmonary and gastrointestinal deposition for each matrix cell were estimated by a two way linear interpolation of equivalent diameter and fiber length. This process was repeated for each of the four assumed fiber configurations.
3. The interpolated pulmonary and gastrointestinal deposition fractions were applied to the number of fibers in that particular cell of the fiber size matrix. This was repeated for each matrix cell and the results summed over all cells. The pulmonary and gastrointestinal fractions were then the ratios of these sums to the total number of fibers sized.

The above steps may be represented mathematically as follows:

$$\text{Pulmonary Fraction (configuration k)} = \sum_{i=1}^r \sum_{j=1}^c f_{ijk} N_{ij} \quad \sum_{i=1}^r \sum_{j=1}^c N_{ij}$$

$$\text{Gastrointestinal Fraction (configuration k)} = \sum_{i=1}^r \sum_{j=1}^c g_{ijk} N_{ij} \quad \sum_{i=1}^r \sum_{j=1}^c N_{ij}$$

Where:

- r = number of rows in the fiber size matrix
- c = number of columns in the fiber size matrix
- $N_{ij}$  = number of fibers in the  $i$ th row and the  $j$ th column of the fiber size matrix
- $f_{ijk}$ ,  $g_{ijk}$  = fraction of fibers deposited in the pulmonary or gastrointestinal spaces for configuration  $k$  according to the deposition model. These values are obtained by interpolation based on aerodynamic diameter and fiber length.

In addition to the above fractional estimates based on counts of all fibers, estimates of deposition for those fibers considered most significant by Stanton (1977) for tumor production in animals were determined. As suggested by Stanton "significant fibers" were considered to be those  $\geq 1.5 \mu\text{m}$  in physical diameter and  $\leq 5.0 \mu\text{m}$  in length.

Finally, estimates of the fiber mass deposited in the pulmonary and gastrointestinal spaces were obtained. Fiber mass was estimated by the assumption that fibers were cylinders with diameters and lengths equal to the midpoints of the size intervals and assuming uniform fiber density. This method was used by Harris and Timbrell (1977) and similar methods have been used to estimate asbestos mass concentrations in air (Selikoff et al, 1972).

## RESULTS

Results of the fractional deposition estimates based on fiber number and mass for all four fiber configurations are given in Appendix D. For purposes of comparing deposition fractions for the various fiber types and industries, a fiber configuration for each fiber type was assumed based on knowledge of the airborne fiber geometry. These assumed configurations are shown in Table 2 and photomicrographs of fibers of each type studied are shown in Appendix E.

Based on these configuration assumptions, estimates of pulmonary and gastrointestinal deposition fractions for all fibers according to fiber number are given in Table 3 and graphically presented in Figure 2. These data show wide variations according to fiber type and industry. In general, the fractions estimated to be deposited in the pulmonary spaces and gastrointestinal tract show more variation according to fiber type than within industries or operations using the same type of fiber. The largest pulmonary fractions were predicted for the amphibole asbestos types (amosite, anthophyllite, and tremolite), wollastonite and fibrous glass microfiber. For each of these fiber types or operations, the estimated pulmonary fraction was 14 to 16% while the fractions for operations using chrysotile ranged from 12% to slightly over 13%. The lowest pulmonary fraction was estimated for mineral wool fibers where only 3% of the fibers were predicted to reach the pulmonary spaces.

The gastrointestinal fiber number fractions also show wide variations. Due to their large aerodynamic equivalent diameters and long lengths, 59% of the mineral wool fibers were predicted to enter the gastrointestinal

Table 2

Assumed Fiber Configurations for  
Comparisons Presented in Text

Fiber Type	Assumed Configuration
Chrysotile	50% S, 50% D
Amosite	0
Anthophyllite	S
Tremolite	0
Wollastonite	0
Mineral Wool	0
Fibrous Glass	S

0 - Single Straight (Ordered)

S - Single Curved (Random)

D - Double, Two Dimensional

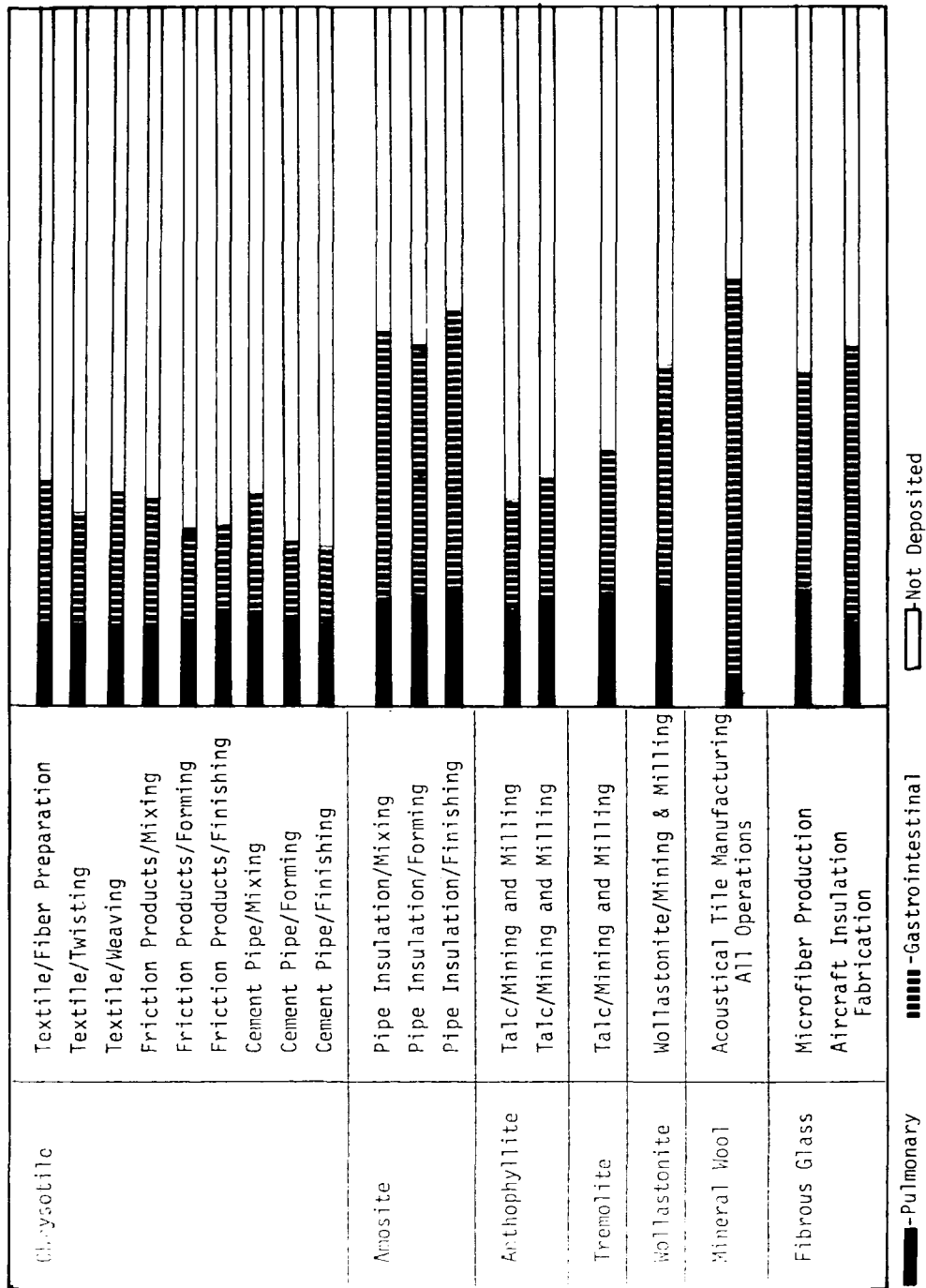
T - Triple, Three Dimensional

Table 3

Estimates of Pulmonary and Gastrointestinal Deposition Fractions  
for all Fibers for Assumed Fiber Configurations

Fiber Type	Industry/Operation	Number Fraction		Mass Fraction	
		Pul.	G.I.	Pul.	G.I.
Chrysotile	Textile/Fiber Preparation	0.13	0.20	0.05	0.60
	Textile/Twisting	0.13	0.16	0.05	0.59
	Textile/Weaving	0.13	0.17	0.05	0.60
	Friction Products/Mixing	0.12	0.13	0.07	0.55
	Friction Products/Forming	0.12	0.13	0.06	0.57
	Friction Products/Finishing	0.13	0.17	0.04	0.60
	Cement Pipe/Mixing	0.13	0.16	0.06	0.58
	Cement Pipe/Forming	0.13	0.13	0.08	0.53
	Cement Pipe/Finishing	0.12	0.11	0.09	0.51
Amosite	Pipe Insulation/Mixing	0.16	0.39	0.06	0.61
	Pipe Insulation/Forming	0.16	0.36	0.05	0.62
	Pipe Insulation/Finishing	0.16	0.41	0.06	0.62
Anthophyllite	Talc/Mining and Milling	0.14	0.18	0.15	0.53
	Talc/Mining and Milling	0.14	0.19	0.14	0.53
Tremolite	Talc/Mining and Milling	0.15	0.21	0.17	0.49
Wollastonite	Wollastonite/Mining & Milling	0.16	0.32	0.06	0.62
Mineral Wool	Acoustic Tile Manufacturing All Operations	0.03	0.59	0.02	0.47
Fibrous Glass	Microfiber Production	0.15	0.33	0.02	0.46
	Aircraft Insulation Fabrication	0.13	0.40	0.02	0.52

Figure 2  
 Estimates of Pulmonary and Gastrointestinal Deposition Fractions by Count for Assumed Fiber Configurations



tract. The gastrointestinal fractions predicted for chrysotile were generally somewhat smaller than for the amphibole asbestos types and considerably smaller than predicted for amosite. It should be noted that, for the same fiber type, significant variations in the gastrointestinal fractions were predicted. For example, gastrointestinal fractions for chrysotile ranged from 0.11 to 0.20, or almost a two fold difference depending on the operation and industry.

The estimated mass fractions shown in Table 3 and Figure 3 also show significant variability. On a mass basis, the gastrointestinal fractions are considerably greater than the number fractions for each fiber type and the pulmonary fractions somewhat smaller. This, of course, is a function of the different fiber sizes deposited or cleared to these sites. It is interesting that the largest pulmonary mass fractions were predicted for anthophyllite and tremolite in talc mining and milling operations. This is due to the combination of small diameters for these fibers and short fiber length resulting in the pulmonary fraction being a larger fraction of the total airborne fiber mass.

As previously discussed, most researchers feel that long, thin fibers may be more important in disease production and Stanton et al (1977) have suggested that fibers less than 1.5  $\mu\text{m}$  in diameter and longer than 8  $\mu\text{m}$  may be most important. It would then be of interest to estimate what fraction of airborne fibers of different types which lie in this "significant" size range and to estimate the pulmonary and gastrointestinal deposition for these fibers.

For purposes of the present study Stanton's size criteria were relaxed and "significant" fibers were defined to be those  $\leq 1.5 \mu\text{m}$  in diameter and  $> 5.0 \mu\text{m}$  in length. The fraction of airborne fibers which satisfy these size criteria for each fiber type, industry or operation are given in Table 4. Also shown in Table 4 is the fraction of the total airborne fiber mass represented by these "significant" fibers. Estimates of the number fractions of these "significant" fibers deposited in the pulmonary spaces and the gastrointestinal tract are given in Table 5 for the assumed fiber configurations and graphically presented in Figure 4.

Table 4 shows that the largest fraction of airborne fibers which fell into the "significant" size range were found in operations producing or using small diameter fibrous glass. In fibrous glass microfiber production, 70% of the airborne fibers were considered significant and 63% in aircraft insulation fabrication. In amosite pipe insulation manufacture, 35 to 41% of the fibers were in the "significant" size range followed by mineral wool where 27% were "significant". The lowest fractions in this size range was 4% for tremolite occurring as a contaminant in talc mining and milling. Operations using chrysotile asbestos showed wide variability in the fractions of these "significant fibers" ranging from 5 to 21%.

Even though large fractions of some fiber types, such as mineral wool, fell within the "significant" size range, very few of these are capable of pulmonary deposition as shown in Table 5 and Figure 4. With the exception of mineral wool and wollastonite, the estimated pulmonary deposition fractions for "significant" fibers were remarkably similar ranging from 12 to 16%.

Figure 3  
 Estimates of Pulmonary and Gastrointestinal Deposition Fractions by Mass for Assumed Fiber Configurations

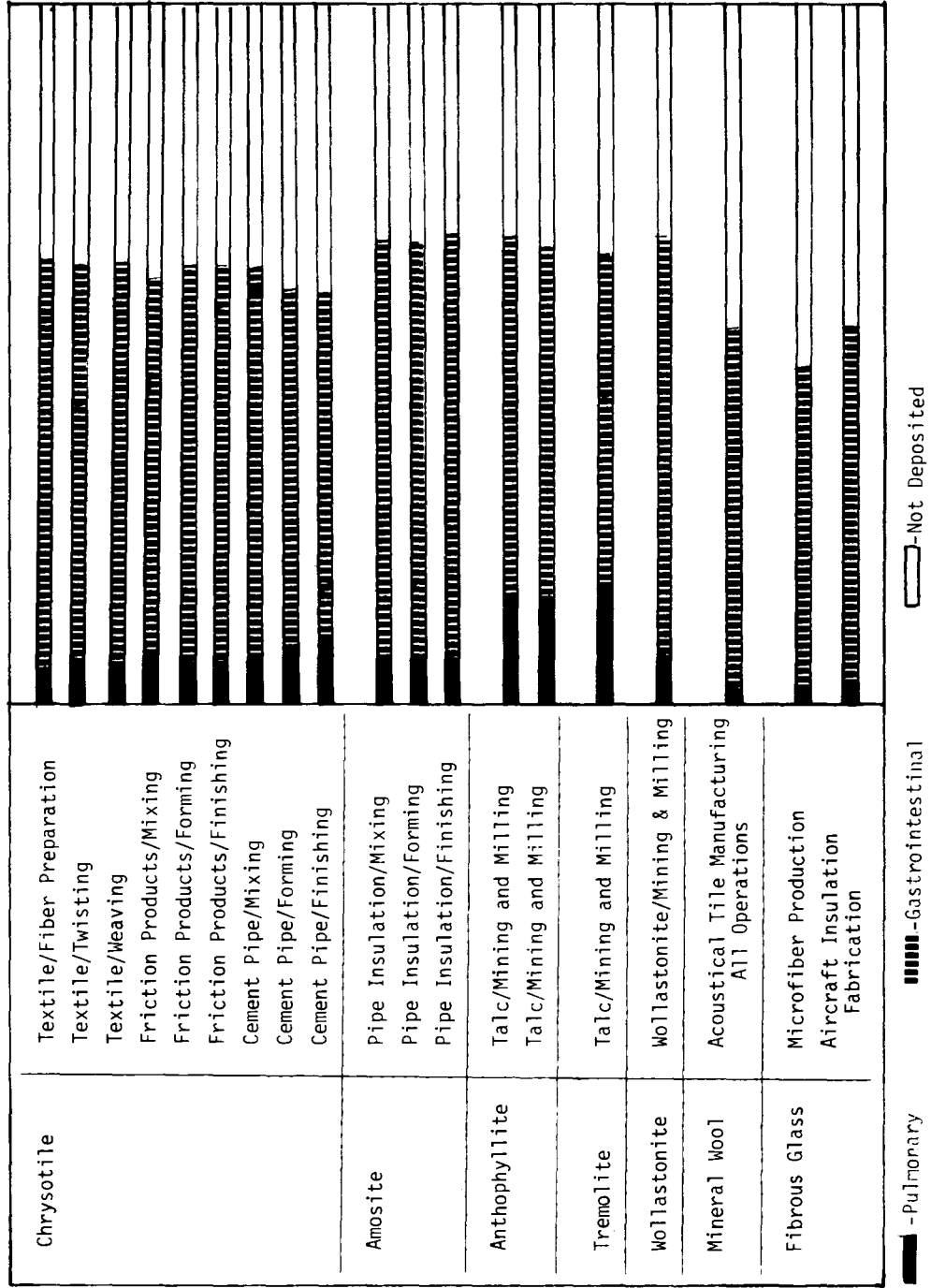


Table 4

Fraction Significant Fibers ( $< 1.5 \mu\text{m}$  Diameter and  $> 5 \mu\text{m}$  in Length)  
by Fiber Type, Industry and Operation

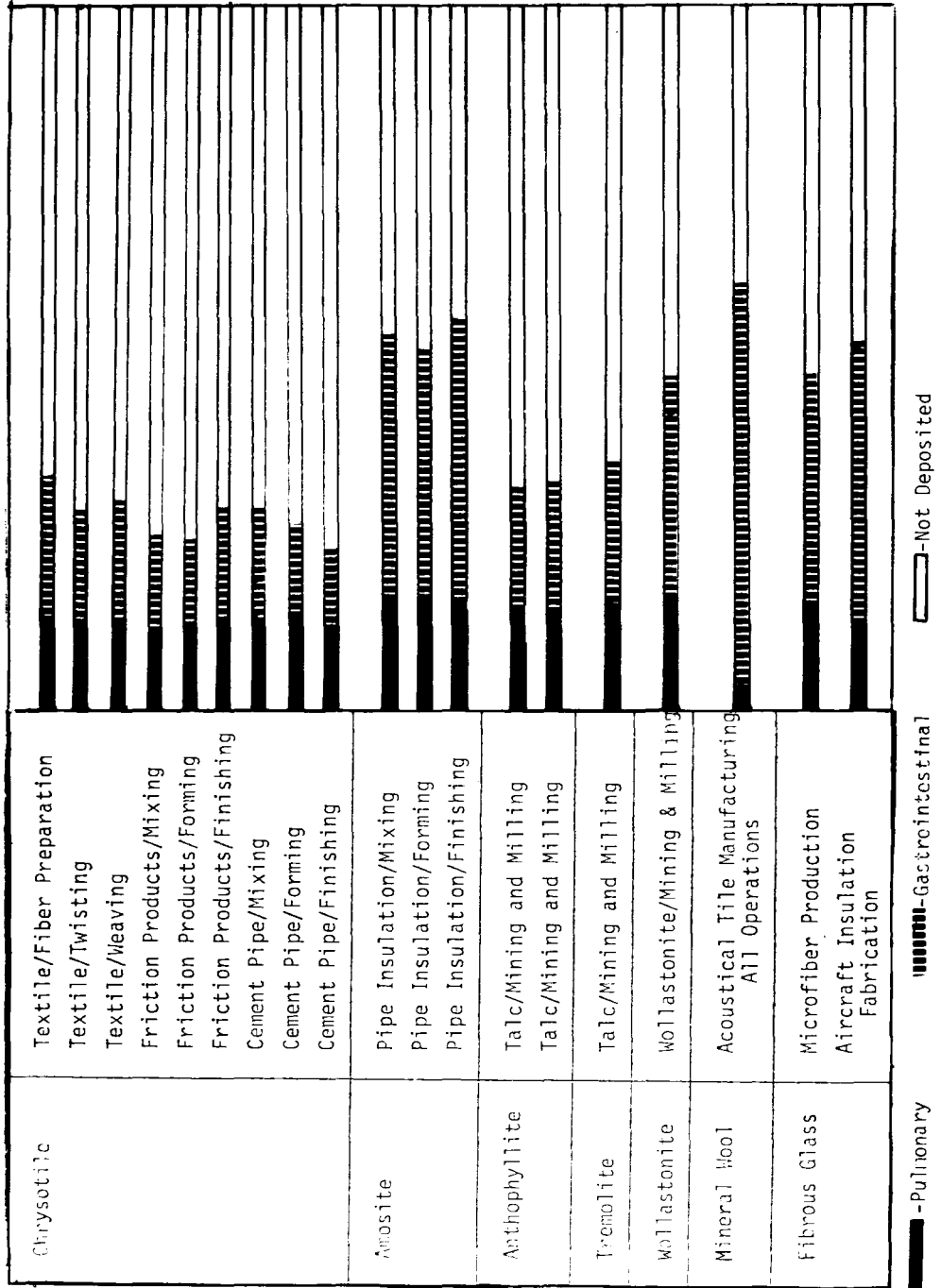
Fiber Type	Industry/Operation	Fraction	
		Count	Mass
Chrysotile	Textile/Fiber Preparation	0.21	0.92
	Textile/Twisting	0.17	0.92
	Textile/Weaving	0.19	0.91
	Friction Products/Mixing	0.10	0.87
	Friction Products/Forming	0.09	0.84
	Friction Products/Finishing	0.16	0.95
	Cement Pipe/Mixing	0.12	0.89
	Cement Pipe/Forming	0.09	0.79
	Cement Pipe/Finishing	0.05	0.83
Amosite	Pipe Insulation/Mixing	0.41	0.84
	Pipe Insulation/Forming	0.37	0.86
	Pipe Insulation/Finishing	0.35	0.84
Anthophyllite	Talc/Mining and Milling	0.11	0.66
	Talc/Mining and Milling	0.12	0.69
Tremolite	Talc/Mining and Milling	0.04	0.22
Wollastonite	Wollastonite/Mining & Milling	0.13	0.78
Mineral Wool	Acoustical Tile Manufacturing All Operations	0.27	0.04
Fibrous Glass	Microfiber Production	0.70	0.12
	Aircraft Insulation Fabrication	0.63	0.12

Table 5

Estimates of Pulmonary and Gastrointestinal Deposition Fractions  
for "Significant Fibers" for Assumed Fiber Configurations

Fiber Type	Industry/Operation	Number Fraction	
		Pul.	G.I.
Chrysotile	Textile/Fiber Preparations	0.12	0.42
	Textile/Twisting	0.14	0.37
	Textile/Weaving	0.13	0.38
	Friction Products/Mixing	0.15	0.30
	Friction Products/Forming	0.15	0.32
	Friction Products/Finishing	0.12	0.41
	Cement Pipe/Mixing	0.14	0.37
	Cement Pipe/Forming	0.15	0.28
	Cement Pipe/Finishing	0.15	0.30
Amosite	Pipe Insulation/Mixing	0.13	0.48
	Pipe Insulation/Forming	0.14	0.47
	Pipe Insulation/Finishing	0.12	0.51
Anthophyllite	Talc/Mining and Milling	0.16	0.44
	Talc/Mining and Milling	0.16	0.43
Tremolite	Talc/Mining and Milling	0.16	0.44
Wollastonite	Wollastonite/Mining & Milling	0.07	0.62
Mineral Wool	Acoustic Tile Manufacturing All Operations	0.05	0.60
Fibrous Glass	Microfiber Production	0.15	0.35
	Aircraft Insulation Fabrication	0.14	0.41

Figure 4  
 Estimates of Pulmonary and Gastrointestinal Deposition Fractions by Count for "Significant" Fibers for Assumed Fiber Configurations



For mineral wool and wollastonite, pulmonary deposition fractions of 5 and 7% were observed, respectively. The gastrointestinal fractions estimated for significant fibers showed more variability ranging from 62% for wollastonite to 28% for chrysotile in cement pipe forming operations.

The analytical method which has generally been used for routine evaluation of occupational fiber exposures is phase contrast optical microscopy as recommended for asbestos (NIOSH, 1972) and fibrous glass (NIOSH, 1977). The usual practice is to count only those fibers which exceed 5  $\mu\text{m}$  in length. The 5  $\mu\text{m}$  length designation is necessary with this method due to resolution limits of the optical microscope and difficulty in distinguishing fibers  $<5 \mu\text{m}$  in length from other particles.

There are two important factors to consider when evaluating fiber exposure data from various industries as determined by phase contrast optical microscopy. First, is the fact that large portions of the airborne fibers may be shorter than 5  $\mu\text{m}$  in length and therefore not included in the fiber concentrations presented. In fact, the fractions of fibers which exceed 5  $\mu\text{m}$  are extremely variable. For example, for the present study, 91% of the mineral wool fibers were longer than 5  $\mu\text{m}$  as opposed to only 4% of the tremolite fibers occurring in talc mining and milling. Secondly, the fraction of airborne fibers deposited in the pulmonary spaces or cleared to the gastrointestinal tract vary considerably according to fiber type and industrial operation.

The final analyses undertaken in the present study was to estimate pulmonary and gastrointestinal fiber concentrations which might be experienced by workers in each industry given an airborne concentration of 1.0 fibers longer than 5  $\mu\text{m}$  in length per cubic centimeter of air as determined by phase contrast microscopy. These analyses were undertaken to predict concentrations of all fibers and fibers considered "significant" (i.e.  $\leq 1.5 \mu\text{m}$  in diameter and  $\geq 5 \mu\text{m}$  in length). Results of these estimates for all fibers and "significant" fibers are shown in Tables 6 and 7, respectively.

On a total fiber basis, highest pulmonary and gastrointestinal fiber concentrations were predicted for tremolite in talc mining and milling. This is due to the fact that only 4% of these fibers exceed 5  $\mu\text{m}$  in length thus only a small fraction of the fibers would be included in phase contrast fiber counts. The lowest pulmonary concentrations of 0.03 fibers/cc was observed for mineral wool. Pulmonary concentrations of chrysotile fibers varied over an approximately 4 fold range depending on industry and operation.

The estimated pulmonary and gastrointestinal concentrations of significant fibers (Table 7) show some interesting trends. The pulmonary concentrations for chrysotile and amosite were somewhat similar ranging from 0.11 to 0.14 fibers/cc. However, the gastrointestinal concentrations for amosite were considerably higher than for chrysotile. The highest pulmonary concentrations were predicted for anthophyllite and tremolite in talc mining and milling while the lowest was predicted for mineral wool. The gastrointestinal concentration for mineral wool was also the lowest while that for wallastonite was the highest.

Table 6

Estimated Pulmonary and Gastrointestinal Equivalent Fiber Exposures for an Airborne Fiber Concentration of 1.0 Fibers Longer Than 5  $\mu\text{m}$  in Length Per Cubic Centimeter

Fiber Type	Industry/Operation	% $>$ 5 $\mu\text{m}$ in Length	Conc. (fibers/cc)*	
			Pul.	G.I.
Chrysotile	Textile/Fiber Preparation	21	0.62	0.95
	Textile/Twisting	17	0.76	0.94
	Textile/Weaving	19	0.68	0.89
	Friction Products/Mixing	10	1.20	1.30
	Friction Products/Forming	9	1.33	1.44
	Friction Products/Finishing	17	0.76	1.00
	Cement Pipe/Mixing	13	1.00	1.23
	Cement Pipe/Forming	10	1.30	1.30
	Cement Pipe/Finishing	5	2.40	2.20
Amosite	Pipe Insulation/Mixing	41	0.38	0.95
	Pipe Insulation/Forming	37	0.44	0.98
	Pipe Insulation/Finishing	35	0.45	1.17
Anthophyllite	Talc/Mining and Milling	11	1.27	1.63
	Talc/Mining and Milling	12	1.16	1.58
Tremolite	Talc/Mining and Milling	4	3.75	5.25
Wollastonite	Wollastonite/Mining & Milling	13	1.23	2.46
Mineral Wool	Acoustical Tile Manufacturing All Operations	91	0.03	0.65
Fibrous Glass	Microfiber Production	77	0.19	0.43
	Aircraft Insulation Fabrication	85	0.15	0.47

\*Concentrations are for Fibers of all lengths.

Table 7

Estimated Pulmonary and Gastrointestinal Exposures to "Significant Fibers"  
for an Airborne Fiber Concentration of 1.0 Fibers Longer Than  
5  $\mu\text{m}$  in Length Per Cubic Centimeter

Fiber Type	Industry/Operation	% Sig. Fibers	Conc. (fibers/cc)**	
			Pul.	G.I.
Chrysotile	Textile/Fiber Preparation	21	0.12	0.42
	Textile/Twisting	17	0.13	0.36
	Textile/Weaving	19	0.13	0.37
	Friction Products/Mixing	10	0.14	0.29
	Friction Products/Forming	9	0.15	0.33
	Friction Products/Finishing	16	0.11	0.39
	Cement Pipe/Mixing	12	0.14	0.35
	Cement Pipe/Forming	9	0.14	0.26
	Cement Pipe/Finishing	5	0.15	0.30
Amosite	Pipe Insulation/Mixing	41	0.13	0.48
	Pipe Insulation/Forming	37	0.14	0.47
	Pipe Insulation/Finishing	35	0.12	0.51
Anthophyllite	Talc/Mining and Milling	11	0.16	0.44
	Talc/Mining and Milling	12	0.16	0.43
Tremolite	Talc/Mining and Milling	4	0.16	0.44
Wollastonite	Wollastonite/Mining & Milling	13	0.07	0.61
Mineral Wool	Acoustical Tile Manufacturing All Operations	27	0.02	0.18
Fibrous Glass	Microfiber Production	70	0.14	0.32
	Aircraft Insulation Fabrication	63	0.11	0.30

\*Significant fibers defined as those both  $\leq 1.5 \mu\text{m}$  in diameter and  $\geq 5.0 \mu\text{m}$  in length, % by count.

\*\*Concentration of Significant fibers.

It is noteworthy that the estimated pulmonary concentrations of significant fibers for operations producing or using small diameter fibrous glass were very similar to those predicted for chrysotile and amosite asbestos operations.

## DISCUSSION

Although results of the deposition estimates presented in this study should not be taken as strictly quantitative, they are sufficient to demonstrate different deposition patterns between the fiber types and industrial operations studied. These results, combined with knowledge of fiber exposure characteristics and levels, should be a useful tool in evaluating and comparing results from epidemiologic studies.

Some interesting contrasts and comparisons can be made. While occupational asbestos fiber exposures have shown excess risks for both respiratory and gastrointestinal cancer, studies of mortality among fibrous glass production workers have not shown these disease patterns (Enterline and Henderson, 1975; Bayliss et al, 1976; Enterline et al, 1977). All studies of fibrous glass workers have been conducted among cohorts exposed to airborne fiber concentrations typically less than 0.2 fibers longer than 5  $\mu\text{m}$  per cubic centimeter of air with airborne fiber sizes similar to the mineral wool fibers included in the present study (Corn and Sansone, 1974; Dement, 1976; Konzen, 1976; Esmen et al, 1978). On the other hand, reports of respiratory and gastrointestinal cancer among asbestos workers have been based on study cohorts with much higher fiber exposures; perhaps 10-20 fibers longer than 5  $\mu\text{m}$  per cubic centimeter of air (NIOSH, 1972). Thus differences in fiber concentrations combined with different deposition patterns and the fraction of fibers counted for these fiber types would result in pulmonary chrysotile asbestos fiber exposures (all lengths) 1000 to 8000 times those for fibrous glass and gastrointestinal exposures 70 to 300 times greater. In terms of "significant fibers" (i.e. those  $\leq 1.5 \mu\text{m}$  in diameter and  $\geq 5.0 \mu\text{m}$  in length), the pulmonary asbestos fiber concentrations would be 200 to 700 times that for fibrous glass while the gastrointestinal exposure would be 70 to 200 times larger. Even assuming a linear, no threshold model for cancer risk with increasing dose, it is possible that cancer risks associated with fibrous glass exposure, if present, may not be measurable without extremely large cohorts for study. In addition, it has been hypothesized that cancer induction periods may be lengthened by lower exposure levels (Enterline and Henderson, 1975; Seidman, et al, 1977). Since fibrous glass production began in this country in the late 1930's, it is possible that insufficient numbers of workers have survived the required latency period.

Occupational exposures to fibrous glass of small fiber diameter ( $<1 \mu\text{m}$ ) poses additional difficulty. Occupational exposures to these fibers have been found to be much higher than found in other fibrous glass operations, ranging from about 1 to 22 fibers per cubic centimeter (Dement, 1976) and results of the present study have shown estimated pulmonary deposition fractions to be similar to those obtained for chrysotile asbestos. Unfortunately, there are no epidemiologic data available for workers exposed to these materials as commercial production began only in the mid-1960's (NIOSH, 1977).

Commercial production of mineral wool (rock wool and slag wool) began some 30 years earlier than did that of fibrous glass in the United States. There are several large epidemiologic studies underway concerning the mortality experience of workers producing and using these fibers and preliminary results of one study have been reported. Ness et al (1977) reported excess risks of both pulmonary and gastrointestinal cancer among workers producing slag wool and rock wool after 30 or more years latency. Although these data are only preliminary, it is noteworthy that only 3% of these fibers were estimated by the present study to reach the pulmonary spaces while 59% were estimated to enter the gastrointestinal tract. Fiber exposures in mineral wool production facilities have been shown to be considerably higher than in facilities producing fibrous glass (Ness et al, 1977; Esmen et al, 1978). Esmen et al (1978) estimated historic exposure in such plants to range from 0.5 to 1.0 fibers per cubic centimeter of air.

While the present study demonstrated large differences in fiber deposition between fiber types such as asbestos and mineral wool, it should also be noted that rather large variations were noted between the various asbestos minerals studied; particularly between amosite and chrysotile. In general, the numerical fractions estimated to be deposited in the pulmonary spaces was approximately 25% higher for amosite while the gastrointestinal fraction for amosite was 2-3 times that for chrysotile. Most epidemiologic studies demonstrating excess gastrointestinal cancer risk with asbestos exposure have been conducted among cohorts exposed to mixed fiber types (IARC, 1977).

## SUMMARY AND CONCLUSIONS

A mathematical model for deposition of fibrous particles in the human respiratory system was used to estimate pulmonary and gastrointestinal fiber deposition fractions for 7 fiber types covering 19 industries or industrial operations. Although the deposition fractions obtained should not be considered entirely quantitative, the results show the numerical fractions of fibers estimated to be deposited in the pulmonary spaces to range from approximately 3% to 16% and the gastrointestinal fraction to range from approximately 11% to 59% depending on fiber type and industrial operation. Even for the same fiber type, considerable variability in deposition patterns were demonstrated.

While there is a considerable body of animal data now available which suggests that many fiber types can produce fibrosis and tumors in animals when implanted or injected, the exact fiber dimensions necessary for these pathologic responses remain unknown. Further research to establish these size criteria are of prime importance. It may be possible that critical fiber dimensions differ depending on site of fiber deposition such as the pulmonary or gastrointestinal tract.

In the absence of human epidemiologic data for many types of fibrous materials, knowledge of critical fiber sizes combined with estimates of fiber deposition may provide useful tools for assessing possible health effects from exposure to fibrous particles. Differences in fiber clearance must also be taken into consideration. The fact that large fractions of most fiber types are predicted to enter the gastrointestinal tract combined with data demonstrating an increased cancer risk at these sites among asbestos workers suggest that greater attention be given to deposition at these sites.

## REFERENCES

- Bayliss, D., J. Dement, J.K. Wagoner and H.P. Blejer. 1976. Mortality Patterns Among Fibrous Glass Production Workers. *Ann. N.Y. Acad. Sci.* 271:324-335.
- Corn, M and E.B. Sansone. 1974. Determination of Total Suspended Particulate Matters and Airborne Fiber Concentrations at three Fibrous Glass Manufacturing Facilities. *Environ. Res.* 8:37-52.
- Davis, J.M.G. 1972. The Fibrogenic Effects of Mineral Dusts Injected into the Pleural Cavity of Mice. *Br. J. Exp. Pathol.* 58:190.
- Dement, J.M. 1976. Environmental Aspects of Fibrous Glass Production and Utilization. *Envr. Res.* 9:295-312.
- Enterline, P.E. and V. Henderson. 1975. The Health of Retired Fibrous Glass Workers. *Arch. Environ. Health.* 30:113-116.
- Enterline, P.E. and V. Henderson. 1975. Modeling the Epidemiology of Industrially Induced Cancer. Presented at annual meeting of the American Public Health Association, Chicago, Nov. 18.
- Enterline, P.E. 1977. Mortality Patterns Among Fibrous Glass Production Workers. Presented at SOEH Conference: Occupational Exposures to Fibrous and Particulate Dust and their Extension into the Environment. Washington, D.C., Dec. 4-7.
- Esmen, N.A., Y.Y. Hammad, M. Corn, D. Whittier, N. Kotsko, M. Haller and R.A. Kahn. 1978. Exposure of Employees to Man-Made Mineral Fibers: Mineral Wool Production. *Envr. Res.* 15:262-277.
- Findeisen, W. 1935. The Deposition of Small Airborne Particles in the Human Lung During Respiration. *Pfluegers Archiv Fuer Die Gesamte Physiologie des Menschen and der Tiero.* 236:367-379.
- Goldsmith, H.L. and S.G. Mason. 1962. The Flow of Suspensions Through Tubes, I. Single Spheres, Rods and Discs. *J. Colloid Sci.* 17:448.
- Harris, R.L. and D.A. Fraser. 1976. A Model for Deposition of Fiber in the Human Respiratory System. *Amer. Ind. Hyg. Assoc. J.* 37:73-89.
- Harris, R.L. and V. Timbrell. 1977. The Influence of Fiber Shape in Lung Deposition - Mathematical Estimates. In: W.H. Walton, Ed. *Inhaled Particles IV.* Pergamon Press, Oxford, pp. 75-89.
- Hill, J.W., W.S. Whitehead and J.D. Cameron. 1973. Glass Fibers - Absence of Pulmonary Hazard in Production Workers. *Brit. J. Ind. Med.,* 30:174-179.

- International Agency for Research on Cancer. 1977. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemicals to Man. WHO. Vol. 14, Lyon, France.
- Kuschner, M. and G.W. Wright. 1976. The Effects of Intratracheal Instillation of Glass Fiber of Varying Size in Guinea Pigs. In: Occupational Exposures to Fibrous Glass - Proceedings of A Symposium. USDHEW, National Institute for Occupational Safety and Health, HEW Publication No. (NIOSH) 76-151.
- Lynch, K.M. and W.A. Smith. 1935. Pulmonary Asbestos III. Carcinoma of the Lung in Asbestos - Silicosis. Amer. J. Cancer 24:56-64.
- Merewether, E.R.A. and C.W. Price. 1930. Report on the Effects of Asbestos Dust on the Lungs and Dust Suppression in the Asbestos Industry, London, HMSO.
- Murray, H.M. 1907. In: Report of the Departmental Committee on Compensation for Industrial Disease, Minutes of Evidence, Appendices and Index 3495-3496, London, Wyman and Sons.
- Nasr, A.N.M., T. Ditchek and P.A. Schottens. 1971. The Prevalence of Radiographic Abnormalities in the Chests of Fibrous Glass Workers. J. Occup. Med. 13:371-376.
- Ness, O.G., J.M. Dement, R.J. Waxweiler and J.K. Wagoner. 1977. A Preliminary Report of the Mortality Patterns and Occupational Exposures of a Cohort of Mineral Wool Production Workers. Presented at SOEH Conference: Occupational Exposures to Fibrous and Particulate Dust and their Extension into the Environment. Washington, D.C., Dec. 4-7.
- NIOSH. 1972. Criteria for a Recommended Standard - Occupational Exposure to Asbestos. USDHEW, National Institute for Occupational Safety and Health, Publication No. HSM 72-10267.
- NIOSH. 1977. Criteria for a Recommended Standard - Occupational Exposure to Fibrous Glass. USDHEW, National Institute for Occupational Safety and Health, DHEW (NIOSH) Publication No. 77-152.
- Pott, F. and K.H. Friedrichs. 1972. Tumors in Rats After Intraperitoneal Injection of Fibrous Dust.1 Naturwissenschaften 59:318 (Ger).
- Pott, F., K.H. Friedrichs and F. Huth. 1976. Ergebnisse aus Tierversuchess zur Kanzerogenen Wirkung Faserformiger Staube und ihre Deutung in Hinblick auf die Tumorentstehung beim Menschen. Zbl. Bakt. Hyg., I Abt. Orig. B. 162:467-505.
- Schneiderman, M.A. 1974. Digestive System Cancer Among Persons Subjected to Occupational Inhalation of Asbestos Particles: A Literature Review with Emphasis on Dose Response. Environm. Hlth. Perspect 9:307-311.

- Seidman, H. R. Lilis and I.J. Selikoff. 1977. Short Term Asbestos Exposure and Delayed Cancer Risk. In: Proceedings of Third International Symposium on the Detection and Prevention of Cancer, New York.
- Selikoff, I.J., W.J. Nicholson and A.M. Langer. 1972. Asbestos Air Pollution. Arch. Env. Environ. Health 25:1-13.
- Smith, H.V. 1976. History, Processes, and Operations in the Manufacturing and Uses of Fibrous Glass - One Company's Experience. In: Occupational Exposure to Fibrous Glass - Proceedings of a Symposium. USDHEW, National Institute for Occupational Safety and Health, HEW Publication No. (NIOSH) 76-151.
- Stanton, M.F., M. Layard, M. Miller, M. May and E. Kent. 1977. Carcinogenicity of Fibrous Glass: Pleural Response in the Rat in Relations to Fiber Dimension. J. Natl. Cancer Inst. 58:587-603.
- Task Group on Lung Dynamics. 1966. International Committee on Radiological Protection, P. Marrow, Chairman. Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract. Health Physics 12:173.
- Timbrell, V. 1975. The Inhalation of Fibrous Dusts. Ann. N.Y. Acad. Sci. 132:255-273.
- Utidjan, H.M.D. 1968. Statistical Studies of Health of Fibrous Glass Workers. Read Before the Fibrous Dusts Seminar at the Industrial Health Foundations and Mellon Institute, Pittsburgh.
- Wagner, J.C., C.A. Sleggs and P. Marchand. 1960. Diffuse Pleural Mesothelioma and Asbestos Exposure in the North Western Cape Province. Brit. J. Industr. Med. 17:260-271.
- Wagner, J.C., G. Berry and J.W. Skidmore. 1976. Studies of the Carcinogenic Effects of Fiber Glass of Different Diameters Following Intrapleural Inoculating in Experimental Animals. In: Occupational Exposure to Fibrous Glass - Proceedings of a Symposium. USDHEW, National Institute for Occupational Safety and Health, HEW Publication No. (NIOSH) 76-151.
- Weibel, E.R. 1963. Geometry and Dimensions of Airways of Conductive and Transitory Zones. Morphometry on the Human Lung, Academic Press, New York, pp. 110-143.
- Wright, G.W. 1968. Airborne Fibrous Glass Particles - Chest Roentgenograms of Persons with Prolonged Exposure. Arch. Environ. Health 16:175-181.
- Zumwalde, R.D. and J.M. Dement. 1977. Review and Evaluation of Analytical Methods for Environmental Studies of Fibrous Particulate Exposures. USDHEW, National Institute for Occupational Safety and Health, DHEW (NIOSH) Publication No. 77-204.

APPENDIX A

Mathematical Expressions for Fiber Deposition  
Probability by Deposition Mechanism

The following are mathematical expressions for the probability that a fibre entering an airway will escape deposition by a particular mechanism in that airway without regard to other deposition mechanisms. The individual probabilities of deposition are combined in the model using the special rules of addition of probabilities to obtain the probability of deposition by all mechanisms. The sources or derivations of the basic mathematical relationships are given elsewhere (HARRIS and FRASER, 1976).

*Nasopharynx*

$$N_p = (1 - 2j/S)^7 \left\{ -1.75 - 0.206 \ln \left[ \frac{d^2 q}{\frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}}} \right] \right\}$$

$N_p$  = probability of escape in a single pass through the nasopharynx (assume 7 stages of nasal hairs),

$j$  =  $\frac{1}{2}$  average projected length of particle,

rod:  $j = l_r/4$ ,

disc:  $j = \pi l_r/8$ ,

sphere:  $j = l_r/2$ ,

$l_r$  = length of elemental rod, cm,

$S$  = spacing between nasal hairs, 0.035 cm,

$d$  = diameter of elemental rod, cm,

$q$  = airflow rate in airway,  $\text{cm}^3/\text{s}$ ,

$\beta$  = axis ratio of elemental rod,  $l_r/d$ .

*Sedimentation in Airway*

*Turbulent flow:*

$$S_t = \exp - \frac{1.57 U_t l_z}{\pi \bar{U} (r_z - j)}$$

*Laminar flow:*

$$S_t = (2/\pi) (c^{1/3} \sqrt{1 - c^{2/3}} - 2c \sqrt{1 - c^{2/3}} + \sin^{-1} \sqrt{1 - c^{2/3}}),$$

$c < 1$  (when  $c \geq 1$ ,  $S_t = 0$ ),

$$c = \frac{3U_t l_z r_z^2 (0.785)}{8\bar{U} (r_z - j)^3}$$

$S_t$ ,  $S_l$  = fraction of entering particles which escape deposition by sedimentation,

$U_t$  = terminal settling velocity of particle,  $\text{cm/s}$ ,

$$U_t = \frac{d^2 g}{8\eta \left[ \frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}} \right]}$$

$l_z$  = length of airway, cm,

$r_z$  = radius of airway, cm,

$\bar{U}$  = mean air velocity in airway,  $\text{cm/s}$ ,

$\eta$  = viscosity of air in airway, poise,

$g$  = gravitational constant,  $\text{cm/s}^2$ ,

### Diffusion in Airway

*Turbulent flow:*

$$D_t = 1 - \frac{D l_z \text{Re}^{7/8}}{50 \bar{U} r_z^2}$$

*Laminar flow:*

$$D_t = 4.07h^{2/3} - 2.4h - 0.44h^{4/3},$$

$D_t, D_l$  = fraction of entering particles which escape deposition by diffusion,

$D$  = diffusion coefficient,  $\text{cm}^2/\text{s}$ ,

$$D = \frac{3.6 \times 10^{-11}}{l_z n \left[ \frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}} \right]},$$

$\text{Re}$  = Reynolds number of air in airway,

$$h = \frac{l_z \pi D}{2q},$$

$n$  = number of elemental rods in compound particle ( $n = 1$  for single, 2 for double, and 3 for triple).

### Impaction and Interception in Airway

*Turbulent flow:*

$$I_{t,z+1} = 1 - \frac{2}{\pi r_z^2} \left[ (s+j) \sqrt{r_z^2 - (s+j)^2} + r_z^2 \sin^{-1} \left( \frac{s+j}{r_z} \right) \right].$$

*Laminar flow:*

$$I_{t,z+1} = 1 - \frac{16}{3\pi} \left[ \left( \frac{3}{8r_z} - \frac{7c^2}{8r_z} - \frac{jc}{4r_z^2} \right) \sqrt{2jcr_z + c^2 r_z^2} + \frac{3jc^2}{r_z} + 2c^3 + \left( \frac{3}{8} - \frac{3c^2}{4} - \frac{9c^4}{8} - \frac{3jc^3}{r_z} + \frac{3j^2 c^2}{2r_z^2} \right) \sin^{-1} \left( \frac{1}{\sqrt{1 + \frac{2jc}{r_z} + c^2}} \right) \right],$$

$I_{t,z+1}, I_{i,z+1}$  = fraction of particles leaving generation  $z$  which escape deposition by impaction and interception on the bifurcation at the entrance to generation  $z + 1$ ,

$s$  = inertial displacement,  $\text{cm}$ ,

$$s = \frac{d^2 \bar{U}_z \sin \lambda}{8\eta \left[ \frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}} \right]},$$

$\lambda$  = angle between initial and final direction of airstream,

$$c = \frac{2r_z \eta}{d^2 \bar{U} \sin \lambda} \left[ \frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}} \right].$$

### Alveolar Deposition

*Interception:*

$$I_a = \left(\frac{r_0 - j}{r_0}\right)^2 \text{ when } r_0 > j, \text{ when } j \geq r_0 \text{ then } I_a = 0.$$

$I_a$  = fraction of particles entering alveolar opening which escape deposition by interception,

$r_0$  = radius of alveolar opening, cm.

*Sedimentation:*

$$S_a = \frac{4.85 \times 10^5 d^2 t}{(r_a - j) \left[ \frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}} \right]} - \frac{1}{2} \left\{ \frac{3.23 \times 10^5 d^2 t}{(r_a - j) \left[ \frac{0.385}{\ln(2\beta) - \frac{1}{2}} + \frac{1.23}{\ln(2\beta) + \frac{1}{2}} \right]} \right\}^3$$

when calculated value of  $S_a > 1$  then  $S_a = 1$ ,

$t$  = time of settling in alveolus, s,

$r_a$  = radius of alveolus, cm,

$S_a$  = fraction of particles entering an alveolus which deposit there by sedimentation.

*Diffusion:*

$$D_a = \exp - \frac{D \pi^2 t}{r_a^2},$$

$D_a$  = fraction of particles entering an alveolus which deposit there by diffusion.



APPENDIX C

Raw Airborne Fiber Length and Diameter Size Data  
by Fiber Type, Industry and Operation

Table C-1

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE**

**INDUSTRY: TEXTILE PRODUCTS**

**OPERATION: FIBER PREPARATION**

**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

**LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	53	89	351	586	490	330	218	198	113	119	50	80	114	67
0.15	0	0	1	3	63	376	291	164	130	96	66	52	37	58	92	75
0.25	0	0	0	0	6	123	153	161	92	98	67	45	41	36	104	95
0.35	0	0	0	0	1	3	40	56	58	43	24	33	7	21	60	64
0.45	0	0	0	0	0	1	10	5	25	37	19	21	12	11	64	111
0.55	0	0	0	0	0	0	4	5	12	23	6	6	7	6	30	29
0.65	0	0	0	0	0	0	0	1	7	1	7	6	2	5	15	24
0.75	0	0	0	0	0	0	0	2	6	2	4	2	3	5	10	17
0.85	0	0	0	0	0	0	0	0	1	0	0	4	3	2	1	12
0.95	0	0	0	0	0	0	0	1	4	5	6	11	5	16	11	11
1.50	0	0	0	0	0	0	0	1	0	3	5	19	7	8	202	223

Table C-2

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE  
 INDUSTRY: TEXTILE PRODUCTS  
 OPERATION: TWISTING OPERATIONS**

**FIBER SIZE INTERVAL MIDPOINT (MICROMETERS)  
 LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	67	146	574	877	524	336	170	171	88	71	41	62	87	88
0.15	0	0	0	4	46	224	188	123	87	75	47	72	24	27	67	89
0.25	0	0	0	0	8	51	81	64	95	47	27	40	17	22	58	75
0.35	0	0	0	0	0	5	20	18	17	21	14	23	6	10	36	69
0.45	0	0	0	0	0	2	6	20	21	19	11	18	6	18	35	69
0.55	0	0	0	0	0	0	1	1	4	4	3	6	2	4	13	21
0.65	0	0	0	0	0	0	2	0	4	6	5	2	4	4	8	23
0.75	0	0	0	0	0	0	1	1	1	0	1	2	0	2	5	6
0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4
0.95	0	0	0	0	0	0	0	2	0	3	4	10	2	7	20	12
1.50	0	0	0	0	0	0	0	0	2	1	3	2	2	4	49	125

Table C-3

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE  
 INDUSTRY: TEXTILE PRODUCTS  
 OPERATION: WEAVING OPERATIONS  
 FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	34	101	479	696	362	294	167	193	120	113	47	62	79	71
0.15	0	0	0	2	38	193	92	76	50	99	45	35	15	46	88	76
0.25	0	0	0	0	1	33	40	45	18	24	27	30	6	47	69	56
0.35	0	0	0	0	0	1	9	11	6	11	10	11	5	11	19	28
0.45	0	0	0	0	0	1	4	8	11	11	11	31	10	46	55	89
0.55	0	0	0	0	0	0	2	2	7	5	4	1	1	1	8	16
0.65	0	0	0	0	0	0	0	0	2	2	2	3	2	3	7	14
0.75	0	0	0	0	0	0	0	0	1	0	0	4	1	2	5	6
0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
0.95	0	0	0	0	0	0	0	0	0	1	2	6	0	27	7	2
1.50	0	0	0	0	0	0	0	0	0	1	2	8	5	9	51	155

Table C-4

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE**  
**INDUSTRY: FRICTION PRODUCTS**  
**OPERATION: MIXING**

**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

**LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	19	196	402	855	956	571	325	183	158	81	88	39	61	99	63
0.15	0	0	0	0	81	233	178	158	78	75	52	36	13	41	39	95
0.25	0	0	0	0	6	87	80	60	52	35	25	28	11	16	40	49
0.35	0	0	0	0	1	9	11	21	23	18	14	15	5	11	23	37
0.45	0	0	0	0	0	2	11	12	13	10	18	17	8	10	14	34
0.55	0	0	0	0	0	0	1	1	2	5	3	2	1	0	6	7
0.65	0	0	0	0	0	0	0	1	1	2	1	4	1	3	3	11
0.75	0	0	0	0	0	0	0	0	1	1	0	0	2	0	5	2
0.85	0	0	0	0	0	0	0	0	0	1	0	3	1	0	2	3
0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
1.50	0	0	0	0	0	0	0	0	0	0	3	0	0	2	18	37

Table C-5

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE**  
**INDUSTRY: FRICTION PRODUCTS**  
**OPERATION: PRODUCT FORMING**  
**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	85	182	564	683	395	138	98	82	47	59	16	54	44	32
0.15	0	0	0	8	57	174	113	63	46	48	34	40	12	29	48	34
0.25	0	0	0	0	2	19	49	32	28	26	21	29	8	26	27	38
0.35	0	0	0	0	0	0	6	9	5	10	11	8	1	12	13	16
0.45	0	0	0	0	0	0	0	5	4	9	2	15	2	11	19	15
0.55	0	0	0	0	0	1	0	1	1	2	0	0	1	2	4	1
0.65	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	5
0.75	0	0	0	0	0	0	0	0	0	1	1	4	0	1	5	6
0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
0.95	0	0	0	0	0	0	0	0	0	2	0	3	0	6	4	1
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	8	9	31

Table C-6

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE  
 INDUSTRY: FRICTION PRODUCTS  
 OPERATION: PRODUCT FINISHING**

**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

**LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	2	34	86	299	371	224	113	71	128	47	31	12	39	36	21
0.15	0	0	0	2	46	110	75	38	36	57	13	17	4	14	49	14
0.25	0	0	0	0	1	22	27	24	24	38	11	13	4	10	29	20
0.35	0	0	0	0	0	6	3	12	12	18	8	7	4	3	19	6
0.45	0	0	0	0	0	0	4	17	9	18	9	20	6	11	35	29
0.55	0	0	0	0	0	0	0	4	1	3	2	3	1	2	6	7
0.65	0	0	0	0	0	0	1	2	3	3	0	3	2	0	6	6
0.75	0	0	0	0	0	1	0	0	0	1	4	1	0	0	1	3
0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
0.95	0	0	0	0	0	0	0	0	1	2	4	1	0	1	7	0
1.50	0	0	0	0	0	0	0	0	0	0	2	3	2	0	17	124

Table C-7

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE  
 INDUSTRY: CEMENT PIPE  
 OPERATION: MIXING**

**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)  
 LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	24	72	265	353	173	110	65	48	22	25	13	21	15	13
0.15	0	0	0	0	27	126	75	61	39	33	15	27	10	21	35	34
0.25	0	0	0	0	0	60	40	44	32	19	19	14	8	18	28	16
0.35	0	0	0	0	0	0	17	17	13	10	15	13	4	7	20	15
0.45	0	0	0	0	0	0	2	13	8	7	2	2	1	9	15	24
0.55	0	0	0	0	0	0	0	1	4	2	2	0	1	2	2	4
0.65	0	0	0	0	0	0	0	2	0	1	0	2	0	0	5	5
0.75	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	1
0.85	0	0	0	0	0	0	0	0	0	3	0	0	0	0	1	1
0.95	0	0	0	0	0	0	0	0	0	1	0	2	0	3	2	1
1.50	0	0	0	0	0	0	0	0	0	0	0	2	0	3	27	27

Table C-8

AIRBORNE FIBER SIZE DATA

FIBER TYPE: CHRYSOTILE

INDUSTRY: CEMENT PIPE

OPERATION: PRODUCT FORMING

FIBER SIZE INTERVAL MIDPOINT (MICROMETERS)

LENGTH

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	17	42	224	333	399	139	72	77	51	44	18	48	52	28
0.15	0	0	0	0	23	132	96	66	41	47	27	32	7	31	27	24
0.25	0	0	0	0	0	34	46	39	27	22	16	12	5	15	19	11
0.35	0	0	0	0	0	0	14	9	7	7	7	6	3	9	13	4
0.45	0	0	0	0	0	0	1	10	9	11	6	5	4	12	11	19
0.55	0	0	0	0	0	0	0	1	1	0	0	3	0	1	2	2
0.65	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	2
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.95	0	0	0	0	0	0	0	0	0	1	0	0	0	3	2	0
1.50	0	0	0	0	0	0	0	0	0	0	0	1	1	2	4	13

Table C-9

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: CHRYSOTILE**

**INDUSTRY: CEMENT PIPE**

**OPERATION: PRODUCT FINISHING**

**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

**LENGTH**

DIAHETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	8	241	332	852	877	502	227	129	74	44	39	26	40	53	17
0.15	0	0	0	7	54	284	152	89	69	45	30	25	26	19	24	15
0.25	0	0	0	0	0	68	55	36	29	50	32	14	4	11	20	14
0.35	0	0	0	0	0	5	10	15	16	3	5	6	5	4	22	5
0.45	0	0	0	0	0	0	1	4	2	2	6	5	1	12	9	36
0.55	0	0	0	0	0	0	0	0	1	0	0	2	1	0	0	1
0.65	0	0	0	0	0	0	0	0	0	0	0	0	2	1	2	3
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
0.95	0	0	0	0	0	0	0	0	0	0	1	0	0	2	2	2
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13

Table C-10

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: AMOSITE**  
**INDUSTRY: PIPE INSULATION MFG**  
**OPERATION: MIXING**

**FIBER SIZE INTERVAL MIDPOINT (MICROMETERS)**  
**LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.09	0	0	0	0	0	2	4	3	3	1	2	4	1	0	3	0
0.15	0	0	0	0	0	8	10	5	4	3	5	5	2	1	9	4
0.25	0	0	0	0	0	3	8	5	4	7	4	4	2	3	10	7
0.35	0	0	0	0	0	1	2	2	5	1	4	3	3	4	15	4
0.45	0	0	0	0	0	0	3	3	2	2	1	2	2	1	11	10
0.55	0	0	0	0	0	0	3	2	2	4	1	1	2	3	7	8
0.65	0	0	0	0	0	0	0	5	4	4	3	1	3	11	9	9
0.75	0	0	0	0	0	0	0	1	1	0	2	1	1	0	4	2
0.85	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	4
0.95	0	0	0	0	0	0	0	1	0	1	3	0	1	2	2	7
1.50	0	0	0	0	0	0	0	0	0	1	1	2	4	2	6	19

Table C-11

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: AMOSITE  
 INDUSTRY: PIPE INSULATION MFG  
 OPERATION: FORMING**

**FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

**LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	0	0	0	0	3	6	1	2	1	2	2	1	1	0
0.15	0	0	0	0	0	3	6	5	2	4	3	3	3	1	6	1
0.25	0	0	0	0	0	3	8	9	6	2	3	5	3	3	10	8
0.35	0	0	0	0	0	0	4	3	2	3	2	4	2	4	6	9
0.45	0	0	0	0	0	0	4	1	7	2	2	2	0	0	7	5
0.55	0	0	0	0	0	0	1	3	3	1	2	3	1	1	3	5
0.65	0	0	0	0	0	0	1	4	2	1	1	0	0	2	4	4
0.75	0	0	0	0	0	0	0	2	1	0	0	0	0	2	3	3
0.85	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	1
0.95	0	0	0	0	0	0	0	0	0	1	1	0	0	1	2	1
1.50	0	0	0	0	0	0	0	0	0	1	2	0	2	2	6	15

Table C-12

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: AMOSITE  
 INDUSTRY: PIPE INSULATION MFG  
 OPERATION: FINISHING**

**FIBER SIZE INTERVAL MIDPOINT (MICROMETERS)  
 LENGTH**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0.15	0	0	0	0	0	2	3	3	3	6	3	3	2	1	5	0
0.25	0	0	0	0	0	0	6	5	7	4	2	3	4	4	9	1
0.35	0	0	0	0	0	1	1	5	0	3	0	0	3	4	6	3
0.45	0	0	0	0	0	0	1	3	3	1	0	1	0	0	6	1
0.55	0	0	0	0	0	0	1	6	1	3	4	2	2	3	3	3
0.65	0	0	0	0	0	0	0	2	2	3	1	3	2	5	6	4
0.75	0	0	0	0	0	0	0	0	1	0	2	4	0	2	2	3
0.85	0	0	0	0	0	0	0	0	0	2	0	1	0	1	2	2
0.95	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1
1.50	0	0	0	0	0	0	0	0	0	0	2	2	0	2	7	15

Table C-13

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: ANTHOPHYLLITE**  
**INDUSTRY: TALC PRODUCTION**  
**OPERATION: MINING AND MILLING**  
**FIBER SIZE INTERVAL MIDPOINT(MICRCHETERS)**

DIAMETER	0.15	0.44	0.74	1.03	1.32	1.62	1.91	2.20	2.50	2.79	3.23	3.82	4.41	5.00	5.59	15.00
0.03	11	80	38	19	26	7	9	5	0	2	1	0	2	0	0	0
0.09	1	48	52	26	17	15	6	5	7	1	3	1	2	0	2	1
0.05	0	12	20	27	23	13	8	6	6	5	5	1	4	0	4	2
0.20	0	0	2	9	13	9	9	7	2	4	5	3	2	0	4	3
0.26	0	0	5	5	11	14	9	10	6	6	11	0	3	1	6	0
0.32	0	0	0	0	3	2	2	2	2	2	2	2	1	2	3	1
0.38	0	0	1	0	3	4	1	3	3	2	3	1	2	3	0	10
0.44	0	0	0	0	2	3	0	1	5	4	2	0	2	0	5	2
0.50	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0
0.56	0	0	0	0	0	2	0	1	4	2	4	4	5	5	4	4
0.80	0	0	0	0	0	0	0	0	0	3	2	6	2	0	22	8

Table C-14

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: ANTHOPHYLLITE  
 INDUSTRY: TALC PRODUCTION  
 OPERATION: MINING AND MILLING  
 FIBER SIZE INTERVAL MIDPOINT(MICROMETERS)**

DIAMETER	0.15	0.44	0.74	1.03	1.32	1.62	1.91	2.20	2.50	2.79	3.23	3.82	4.41	5.00	5.59	15.00
0.03	5	11	11	5	6	1	1	2	0	2	0	0	0	0	0	0
0.09	0	13	14	11	5	5	7	2	2	3	0	1	1	1	0	0
0.05	0	5	13	14	10	8	5	2	0	1	2	4	2	0	3	0
0.20	0	0	5	1	4	4	4	5	1	3	3	0	4	3	0	0
0.26	0	0	6	5	2	4	3	1	1	4	3	0	1	0	2	1
0.32	0	0	0	0	3	0	0	3	0	0	0	1	0	0	0	1
0.38	0	0	0	0	2	2	6	2	1	1	2	0	0	0	2	4
0.44	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	1
0.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.56	0	0	0	0	0	2	0	1	2	3	4	2	2	0	4	2
0.80	0	0	0	0	0	0	0	0	1	0	0	0	1	0	4	7

Table C-15

AIRBORNE FIBER SIZE DATA

FIBER TYPE: TREMOLITE  
 INDUSTRY: TALC PRODUCTION  
 OPERATION: MINING AND MILLING  
 FIBER SIZE INTERVAL MIDPOINT(MICROCENTERS)

DIAMETER	0.15	0.44	0.74	1.03	1.32	1.62	1.91	2.20	2.50	2.79	3.23	3.82	4.41	5.00	5.59	15.00
0.03	2	10	2	5	2	1	1	0	0	0	0	0	0	0	0	0
0.09	0	13	5	10	6	1	2	3	2	0	1	0	0	1	0	0
0.05	0	3	7	9	11	4	8	2	0	0	1	0	0	0	0	0
0.20	0	0	2	5	8	4	4	1	3	1	1	0	0	0	0	0
0.26	0	0	2	3	6	4	5	2	0	1	0	2	0	0	1	0
0.32	0	0	0	1	1	3	0	4	2	0	1	0	0	0	1	0
0.38	0	0	0	0	2	1	1	4	3	1	0	2	0	0	0	1
0.44	0	0	0	0	0	2	4	2	2	0	2	2	1	0	0	0
0.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0.56	0	0	0	0	0	1	2	1	3	1	4	3	0	0	0	1
0.80	0	0	0	0	0	0	0	0	2	3	2	2	2	0	3	0

Table C-16

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: WOLLASTONITE**  
**INDUSTRY: MINING AND MILLING**  
**OPERATION: ALL OPERATIONS POOLED**  
**FIBER SIZE INTERVAL MIDPOINT (MICROMETERS)**

DIAMETER	0.05	0.15	0.25	0.35	0.45	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	7.50	15.00
0.08	0	0	0	8	21	46	17	14	14	8	2	2	0	1	0	0
0.15	0	0	0	0	1	57	61	48	10	11	3	5	1	0	0	0
0.25	0	0	0	0	0	11	73	67	37	21	10	6	2	4	2	0
0.35	0	0	0	0	0	0	36	46	38	17	17	5	1	7	1	1
0.45	0	0	0	0	0	0	0	24	38	40	24	12	8	5	4	1
0.55	0	0	0	0	0	0	0	0	12	25	25	13	4	9	3	2
0.65	0	0	0	0	0	0	0	0	1	12	21	11	4	8	6	3
0.75	0	0	0	0	0	0	0	0	1	2	6	7	10	9	7	4
0.85	0	0	0	0	0	0	0	0	0	1	1	2	7	13	7	5
0.95	0	0	0	0	0	0	0	0	0	0	2	4	9	30	24	13
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	21	24	64

Table C-17

AIRBORNE FIBER SIZE DATA

FIBER TYPE: MINERAL WOOL  
 INDUSTRY: CEILING TILE MFG  
 OPERATION: ALL OPERATIONS POOLED  
 FIBER SIZE INTERVAL MIDPOINT (MICROMETERS)

DIAMETER	3.20	6.85	13.80	30.00	78.00
0.91	337	254	295	223	31
1.45	291	535	566	382	122
2.08	167	470	812	705	201
2.90	41	285	534	710	253
3.80	1	97	251	462	196
5.05	0	13	108	220	117
7.20	0	0	36	118	76

Table C-18

AIRBORNE FIBER SIZE DATA

FIBER TYPE: FIBROUS GLASS  
 INDUSTRY: MICRO FIBER PRCD.  
 OPERATION: ALL OPERATIONS POOLED  
 FIBER SIZE INTERVAL MIDPCINT(MICROMETERS)

DIAMETER	0.24	0.59	0.83	1.16	1.64	2.32	3.28	4.64	6.56	9.27	13.11	18.54	26.22	50.00
0.24	0	0	27	111	232	354	435	481	489	491	431	385	415	1867
0.59	0	0	4	4	9	19	52	81	90	108	81	70	82	342
0.83	0	0	0	0	0	4	10	14	42	46	48	40	33	165
1.16	0	0	0	0	0	0	1	3	13	11	35	34	29	175
1.64	0	0	0	0	0	0	0	3	6	7	15	18	28	154
2.32	0	0	0	0	0	0	0	0	2	4	6	4	20	86
5.00	0	0	0	0	0	0	0	0	0	3	3	8	18	158

Table C-19

**AIRBORNE FIBER SIZE DATA**

**FIBER TYPE: FIBROUS GLASS**

**INDUSTRY: AIRCRAFT INSULATION**

**OPERATION: ALL OPERATIONS POOLED**

**FIBER SIZE INTERVAL MIDPOINT(MICROCENTES)**

**LENGTH**

DIAMETER	0.24	0.59	0.83	1.16	1.64	2.32	3.28	4.64	6.56	9.27	13.11	18.54	26.22	38.39	65.00
0.24	0	0	14	23	40	66	109	167	157	132	125	134	160	68	29
0.59	0	0	0	0	0	3	17	25	41	37	37	29	69	32	30
0.83	0	0	0	0	0	1	5	14	18	26	27	32	95	43	28
1.16	0	0	0	0	0	0	1	7	11	12	18	31	96	37	22
1.64	0	0	0	0	0	0	0	2	3	9	16	15	84	38	12
2.32	0	0	0	0	0	0	0	0	1	1	2	8	60	25	12
3.28	0	0	0	0	0	0	0	0	0	0	4	5	37	14	2
5.00	0	0	0	0	0	0	0	0	0	0	4	7	39	17	13

APPENDIX D

Estimates of Pulmonary and Gastrointestinal Fiber Deposition  
According to Fiber Type, Industry, Operation and Fiber Configuration

(Significant Fibers are those  $\leq 1.5 \mu\text{m}$  in Diameter and  $\geq 5 \mu\text{m}$  in Length)

Table D-1

<b>FIBER TYPE: CHRYSOTILE</b>		
<b>INDUSTRY: TEXTILE PRODUCTS</b>		
<b>OPERATION: FIBER PREPARATION</b>		
<b>TOTAL FIBERS SIZED 6917</b>		
<b>DEPOSITION, ALL FIBERS BY COUNT</b>		
<b>FIBER CONFIGURATION</b>	<b>PULMONARY FRACTION</b>	<b>GI FRACTION</b>
SINGLE STRAIGHT	0.1388	0.1846
SINGLE CURVED	0.1346	0.1907
DOUBLE, TWO DIMENSIONAL	0.1324	0.2104
TRIPLE, THREE DIMENSIONAL	0.1307	0.2210
<b>DEPOSITION, SIGNIFICANT FIBERS BY COUNT</b>		
<b>FIBER CONFIGURATION</b>	<b>PULMONARY FRACTION</b>	<b>GI FRACTION</b>
SINGLE, STRAIGHT	0.1296	0.4078
SINGLE, CURVED	0.1266	0.4189
DOUBLE, TWO DIMENSIONAL	0.1206	0.4140
TRIPLE, THREE DIMENSIONAL	0.1159	0.4064
<b>FRACTION SIGNIFICANT FIBERS: 0.2069</b>		
<b>DEPOSITION, ALL FIBERS BY MASS</b>		
<b>FIBER CONFIGURATION</b>	<b>PULMONARY FRACTION</b>	<b>GI FRACTION</b>
SINGLE STRAIGHT	0.0512	0.6185
SINGLE CURVED	0.0507	0.6204
DOUBLE, TWO DIMENSIONAL	0.0454	0.5845
TRIPLE, THREE DIMENSIONAL	0.0441	0.5546
<b>DEPOSITION, SIGNIFICANT FIBERS BY MASS</b>		
<b>FIBER CONFIGURATION</b>	<b>PULMONARY FRACTION</b>	<b>GI FRACTION</b>
SINGLE STRAIGHT	0.0440	0.6305
SINGLE CURVED	0.0437	0.6320
DOUBLE, TWO DIMENSIONAL	0.0385	0.5936
TRIPLE, THREE DIMENSIONAL	0.0373	0.5620
<b>FRACTION SIGNIFICANT MASS 0.9215</b>		
<b>ESTIMATED FIBER/MASS RELATIONSHIPS</b>		
<b>FRACTION</b>	<b>FIBERS/MICROGRAM</b>	
ALL FIBERS	250088.2	
SIGNIFICANT FIBERS	56145.3	
FIBERS > 5UM/TOTAL MASS	51738.6	

Table D-2

FIBER TYPE: CHRYSOTILE  
 INDUSTRY: TEXTILE PRODUCTS  
 OPERATION: TWISTING OPERATIONS  
 TOTAL FIBERS SIZED 5817  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1328	0.1463
SINGLE CURVED	0.1295	0.1516
DOUBLE, TWO DIMENSIONAL	0.1273	0.1751
TRIPLE, THREE DIMENSIONAL	0.1265	0.1889

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1431	0.3527
SINGLE, CURVED	0.1392	0.3675
DOUBLE, TWO DIMENSIONAL	0.1335	0.3699
TRIPLE, THREE DIMENSIONAL	0.1283	0.3674

FRACTION SIGNIFICANT FIBERS: 0.1657

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0572	0.6018
SINGLE CURVED	0.0565	0.6044
DOUBLE, TWO DIMENSIONAL	0.0508	0.5687
TRIPLE, THREE DIMENSIONAL	0.0491	0.5398

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0494	0.6164
SINGLE CURVED	0.0489	0.6188
DOUBLE, TWO DIMENSIONAL	0.0434	0.5801
TRIPLE, THREE DIMENSIONAL	0.0417	0.5491

FRACTION SIGNIFICANT MASS 0.9228

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	420071.6
SIGNIFICANT FIBERS	75438.1
FIBERS > 5UM/TOTAL MASS	69614.8

Table D-3

FIBER TYPE: CHRYSOTILE

INDUSTRY: TEXTILE PRODUCTS

OPERATION: WEAVING OPERATIONS

TOTAL FIBERS SIZED 4856

DEPOSITION, ALL FIBERS BY CCUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1301	0.1554
SINGLE CURVED	0.1271	0.1604
DOUBLE, TWO DIMENSIONAL	0.1249	0.1827
TRIPLE, THREE DIMENSIONAL	0.1242	0.1959

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1375	0.3613
SINGLE, CURVED	0.1339	0.3746
DOUBLE, TWO DIMENSIONAL	0.1288	0.3754
TRIPLE, THREE DIMENSIONAL	0.1240	0.3719

FRACTION SIGNIFICANT FIBERS: 0.1878

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0498	0.6135
SINGLE CURVED	0.0492	0.6155
DOUBLE, TWO DIMENSIONAL	0.0440	0.5779
TRIPLE, THREE DIMENSIONAL	0.0427	0.5475

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0423	0.6244
SINGLE CURVED	0.0419	0.6262
DOUBLE, TWO DIMENSIONAL	0.0369	0.5858
TRIPLE, THREE DIMENSIONAL	0.0356	0.5535

FRACTION SIGNIFICANT MASS 0.9151

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	310519.2
SIGNIFICANT FIBERS	63727.6
FIBERS > 5UM/TOTAL MASS	58318.3

Table D-4

FIBER TYPE: CHRYSOTILE

INDUSTRY: FRICTION PRODUCTS

OPERATION: MIXING

TOTAL FIBERS SIZED 6143

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1285	0.1105
SINGLE CURVED	0.1256	0.1147
DOUBLE, TWO DIMENSIONAL	0.1236	0.1418
TRIPLE, THREE DIMENSIONAL	0.1239	0.1586

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1545	0.2785
SINGLE, CURVED	0.1501	0.2959
DOUBLE, TWO DIMENSIONAL	0.1459	0.3094
TRIPLE, THREE DIMENSIONAL	0.1407	0.3140

FRACTION SIGNIFICANT FIBERS: 0.0965

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0745	0.5606
SINGLE CURVED	0.0731	0.5650
DOUBLE, TWO DIMENSIONAL	0.0671	0.5351
TRIPLE, THREE DIMENSIONAL	0.0646	0.5103

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0614	0.5935
SINGLE CURVED	0.0606	0.5973
DOUBLE, TWO DIMENSIONAL	0.0543	0.5620
TRIPLE, THREE DIMENSIONAL	0.0519	0.5334

FRACTION SIGNIFICANT MASS 0.8738

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	1231778.0
SIGNIFICANT FIBERS	136075.4
FIBERS > 5UM/TOTAL MASS	118906.8

Table D-5

FIBER TYPE: CHRYSOTILE

INDUSTRY: FRICTION PRODUCTS

OPERATION: PRODUCT FORMING

TOTAL FIBERS SIZED 3767

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1280	0.1125
SINGLE CURVED	0.1252	0.1165
DOUBLE, TWO DIMENSIONAL	0.1232	0.1433
TRIPLE, THREE DIMENSIONAL	0.1235	0.1599

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1540	0.2950
SINGLE, CURVED	0.1497	0.3104
DOUBLE, TWO DIMENSIONAL	0.1454	0.3216
TRIPLE, THREE DIMENSIONAL	0.1403	0.3250

FRACTION SIGNIFICANT FIBERS: 0.0937

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0671	0.5777
SINGLE CURVED	0.0660	0.5809
DOUBLE, TWO DIMENSIONAL	0.0604	0.5492
TRIPLE, THREE DIMENSIONAL	0.0585	0.5231

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0536	0.6048
SINGLE CURVED	0.0530	0.6077
DOUBLE, TWO DIMENSIONAL	0.0475	0.5704
TRIPLE, THREE DIMENSIONAL	0.0456	0.5406

FRACTION SIGNIFICANT MASS 0.8424

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	1018306.0
SIGNIFICANT FIBERS	113270.9
FIBERS > 5UM/TOTAL MASS	95423.9

Table D-6

FIBER TYPE: CHRYSOTILE

INDUSTRY: FRICTION PRODUCTS

OPERATION: PRODUCT FINISHING

TOTAL FIBERS SIZED 2700

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1299	0.1575
SINGLE CURVED	0.1268	0.1619
DOUBLE, TWO DIMENSIONAL	0.1248	0.1838
TRIPLE, THREE DIMENSIONAL	0.1242	0.1966

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1231	0.4048
SINGLE, CURVED	0.1204	0.4143
DOUBLE, TWO DIMENSIONAL	0.1158	0.4085
TRIPLE, THREE DIMENSIONAL	0.1117	0.4007

FRACTION SIGNIFICANT FIBERS: 0.1619

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0394	0.6240
SINGLE CURVED	0.0390	0.6252
DOUBLE, TWO DIMENSIONAL	0.0347	0.5845
TRIPLE, THREE DIMENSIONAL	0.0340	0.5520

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0332	0.6350
SINGLE CURVED	0.0329	0.6359
DOUBLE, TWO DIMENSIONAL	0.0288	0.5930
TRIPLE, THREE DIMENSIONAL	0.0281	0.5590

FRACTION SIGNIFICANT MASS 0.9489

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	261083.8
SIGNIFICANT FIBERS	44530.3
FIBERS > 5UM/TOTAL MASS	42256.9

Table D-7

FIBER TYPE: CHRYSOTILE  
INDUSTRY: CEMENT PIPE  
OPERATION: MIXING  
TOTAL FIBERS SIZED 2345

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1369	0.1390
SINGLE CURVED	0.1331	0.1443
DOUBLE, TWO DIMENSIONAL	0.1312	0.1688
TRIPLE, THREE DIMENSIONAL	0.1303	0.1831

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1499	0.3504
SINGLE, CURVED	0.1461	0.3645
DOUBLE, TWO DIMENSIONAL	0.1404	0.3681
TRIPLE, THREE DIMENSIONAL	0.1350	0.3665

FRACTION SIGNIFICANT FIBERS: 0.1241

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0642	0.5909
SINGLE CURVED	0.0632	0.5939
DOUBLE, TWO DIMENSIONAL	0.0576	0.5623
TRIPLE, THREE DIMENSIONAL	0.0558	0.5355

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0525	0.6155
SINGLE CURVED	0.0520	0.6179
DOUBLE, TWO DIMENSIONAL	0.0464	0.5821
TRIPLE, THREE DIMENSIONAL	0.0448	0.5523

FRACTION SIGNIFICANT MASS 0.8853

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	615318.6
SIGNIFICANT FIBERS	86254.5
FIBERS > 5UM/TOTAL MASS	76357.2

Table D-8

FIBER TYPE: CHRYSOTILE

INDUSTRY: CEMENT PIPE

OPERATION: PRODUCT FORMING

TOTAL FIBERS SIZED 2555

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1334	0.1134
SINGLE CURVED	0.1299	0.1180
DOUBLE, TWO DIMENSIONAL	0.1286	0.1452
TRIPLE, THREE DIMENSIONAL	0.1281	0.1617

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1548	0.2543
SINGLE, CURVED	0.1505	0.2693
DOUBLE, TWO DIMENSIONAL	0.1481	0.2868
TRIPLE, THREE DIMENSIONAL	0.1436	0.2941

FRACTION SIGNIFICANT FIBERS: 0.0924

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0818	0.5413
SINGLE CURVED	0.0801	0.5457
DOUBLE, TWO DIMENSIONAL	0.0746	0.5195
TRIPLE, THREE DIMENSIONAL	0.0722	0.4970

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0619	0.5887
SINGLE CURVED	0.0610	0.5924
DOUBLE, TWO DIMENSIONAL	0.0553	0.5578
TRIPLE, THREE DIMENSIONAL	0.0531	0.5298

FRACTION SIGNIFICANT MASS 0.7855

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	1452168.3
SIGNIFICANT FIBERS	170753.6
FIBERS > 5UM/TOTAL MASS	134133.7

Table D-9

FIBER TYPE: CHRYSOTILE

INDUSTRY: CEMENT PIPE

OPERATION: PRODUCT FINISHING

TOTAL FIBERS SIZED 4846

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1242	0.0944
SINGLE CURVED	0.1217	0.0975
DOUBLE, TWO DIMENSIONAL	0.1197	0.1257
TRIPLE, THREE DIMENSIONAL	0.1206	0.1437

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1574	0.2815
SINGLE, CURVED	0.1536	0.2948
DOUBLE, TWO DIMENSIONAL	0.1493	0.3074
TRIPLE, THREE DIMENSIONAL	0.1441	0.3119

FRACTION SIGNIFICANT FIBERS: 0.0504

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0904	0.5192
SINGLE CURVED	0.0884	0.5245
DOUBLE, TWO DIMENSIONAL	0.0822	0.4995
TRIPLE, THREE DIMENSIONAL	0.0790	0.4786

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0733	0.5746
SINGLE CURVED	0.0722	0.5793
DOUBLE, TWO DIMENSIONAL	0.0653	0.5457
TRIPLE, THREE DIMENSIONAL	0.0622	0.5191

FRACTION SIGNIFICANT MASS 0.8306

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	2663382.1
SIGNIFICANT FIBERS	161445.0
FIBERS > 5UM/TOTAL MASS	134103.4

Table D-10

FIBER TYPE: AMOSITE

INDUSTRY: PIPE INSULATION MFG

OPERATION: MIXING

TOTAL FIBERS SIZED 373

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1552	0.3885
SINGLE CURVED	0.1513	0.3965
DOUBLE, TWO DIMENSIONAL	0.1455	0.3957
TRIPLE, THREE DIMENSIONAL	0.1412	0.3925

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1340	0.4775
SINGLE CURVED	0.1322	0.4857
DOUBLE, TWO DIMENSIONAL	0.1235	0.4698
TRIPLE, THREE DIMENSIONAL	0.1176	0.4572

FRACTION SIGNIFICANT FIBERS: 0.4075

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0640	0.6121
SINGLE CURVED	0.0636	0.6143
DOUBLE, TWO DIMENSIONAL	0.0573	0.5788
TRIPLE, THREE DIMENSIONAL	0.0551	0.5507

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0544	0.6190
SINGLE CURVED	0.0541	0.6209
DOUBLE, TWO DIMENSIONAL	0.0480	0.5815
TRIPLE, THREE DIMENSIONAL	0.0456	0.5507

FRACTION SIGNIFICANT MASS 0.8373

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	103974.7
SIGNIFICANT FIBERS	50602.7
FIBERS > 5UM/TOTAL MASS	42370.4

Table D-11

FIBER TYPE: AMOSITE  
 INDUSTRY: PIPE INSULATION MFG  
 OPERATION: FORMING  
 TOTAL FIBERS SIZED 277  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1612	0.3638
SINGLE CURVED	0.1566	0.3724
DOUBLE, TWO DIMENSIONAL	0.1514	0.3745
TRIPLE, THREE DIMENSIONAL	0.1466	0.3723

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1350	0.4736
SINGLE, CURVED	0.1328	0.4825
DOUBLE, TWO DIMENSIONAL	0.1239	0.4674
TRIPLE, THREE DIMENSIONAL	0.1178	0.4547

FRACTION SIGNIFICANT FIBERS: 0.3682

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0579	0.6144
SINGLE CURVED	0.0574	0.6166
DOUBLE, TWO DIMENSIONAL	0.0520	0.5808
TRIPLE, THREE DIMENSIONAL	0.0501	0.5521

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0489	0.6233
SINGLE CURVED	0.0486	0.6251
DOUBLE, TWO DIMENSIONAL	0.0433	0.5859
TRIPLE, THREE DIMENSIONAL	0.0413	0.5549

FRACTION SIGNIFICANT MASS 0.8583

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	111433.6
SIGNIFICANT FIBERS	47807.3
FIBERS > 5UM/TOTAL MASS	41033.3

Table D-12

FIBER TYPE: AMOSITE  
 INDUSTRY: PIPE INSULATION MFG  
 OPERATION: FINISHING  
 TOTAL FIBERS SIZED 229  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1585	0.4105
SINGLE CURVED	0.1545	0.4182
DOUBLE, TWO DIMENSIONAL	0.1491	0.4164
TRIPLE, THREE DIMENSIONAL	0.1448	0.4119

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1205	0.5087
SINGLE, CURVED	0.1191	0.5146
DOUBLE, TWO DIMENSIONAL	0.1116	0.4958
TRIPLE, THREE DIMENSIONAL	0.1065	0.4805

FRACTION SIGNIFICANT FIBERS: 0.3493

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0553	0.6221
SINGLE CURVED	0.0550	0.6237
DOUBLE, TWO DIMENSIONAL	0.0499	0.5877
TRIPLE, THREE DIMENSIONAL	0.0484	0.5589

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0425	0.6334
SINGLE CURVED	0.0424	0.6345
DOUBLE, TWO DIMENSIONAL	0.0377	0.5942
TRIPLE, THREE DIMENSIONAL	0.0361	0.5623

FRACTION SIGNIFICANT MASS 0.8401

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	92223.8
SIGNIFICANT FIBERS	38348.0
FIBERS > 5UM/TOTAL MASS	32217.9

Table D-13

FIBER TYPE: ANTHOPHYLLITE  
INDUSTRY: TALC PRODUCTION  
OPERATION: MINING AND MILLING  
TOTAL FIBERS SIZED 849  
DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1385	0.1724
SINGLE CURVED	0.1355	0.1766
DOUBLE, TWO DIMENSIONAL	0.1307	0.1984
TRIPLE, THREE DIMENSIONAL	0.1316	0.2109

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1576	0.4390
SINGLE, CURVED	0.1546	0.4481
DOUBLE, TWO DIMENSIONAL	0.1459	0.4432
TRIPLE, THREE DIMENSIONAL	0.1411	0.4378

FRACTION SIGNIFICANT FIBERS: 0.1095

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1419	0.5218
SINGLE CURVED	0.1403	0.5278
DOUBLE, TWO DIMENSIONAL	0.1301	0.5115
TRIPLE, THREE DIMENSIONAL	0.1254	0.4995

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1280	0.5563
SINGLE CURVED	0.1270	0.5616
DOUBLE, TWO DIMENSIONAL	0.1153	0.5382
TRIPLE, THREE DIMENSIONAL	0.1100	0.5218

FRACTION SIGNIFICANT MASS 0.7138

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	992676.7
SIGNIFICANT FIBERS	152341.2
FIBERS > 5UM/TOTAL MASS	95876.9

Table D-14

FIBER TYPE: ANTHOPHYLLITE  
 INDUSTRY: TALC PRODUCTION  
 OPERATION: MINING AND MILLING  
 TOTAL FIBERS SIZED 318  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1432	0.1807
SINGLE CURVED	0.1397	0.1855
DCUBLE, TWO DIMENSIONAL	0.1354	0.2062
TRIPLE, THREE DIMENSIONAL	0.1354	0.2176

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1497	0.4289
SINGLE CURVED	0.1470	0.4369
DCUBLE, TWO DIMENSIONAL	0.1376	0.4278
TRIPLE, THREE DIMENSIONAL	0.1321	0.4200

FRACTION SIGNIFICANT FIBERS: 0.1132

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1314	0.5253
SINGLE CURVED	0.1299	0.5313
DCUBLE, TWO DIMENSIONAL	0.1190	0.5076
TRIPLE, THREE DIMENSIONAL	0.1130	0.4909

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1153	0.5613
SINGLE CURVED	0.1144	0.5664
DCUBLE, TWO DIMENSIONAL	0.1022	0.5347
TRIPLE, THREE DIMENSIONAL	0.0953	0.5127

FRACTION SIGNIFICANT MASS 0.7681

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	811137.8
SIGNIFICANT FIBERS	119551.2
FIBERS > 5UM/TOTAL MASS	81623.9

Table D-15

FIBER TYPE: TREMOLITE  
INDUSTRY: TALC PRODUCTION  
OPERATION: MINING AND MILLING  
TOTAL FIBERS SIZED 241  
DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1528	0.2057
SINGLE CURVED	0.1489	0.2111
DOUBLE, TWO DIMENSIONAL	0.1450	0.2310
TRIPLE, THREE DIMENSIONAL	0.1442	0.2414

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1584	0.4438
SINGLE, CURVED	0.1554	0.4512
DOUBLE, TWO DIMENSIONAL	0.1468	0.4467
TRIPLE, THREE DIMENSIONAL	0.1422	0.4419

FRACTION SIGNIFICANT FIBERS: 0.0373  
DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1651	0.4874
SINGLE CURVED	0.1628	0.4944
DOUBLE, TWO DIMENSIONAL	0.1544	0.4890
TRIPLE, THREE DIMENSIONAL	0.1515	0.4847

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1414	0.5499
SINGLE CURVED	0.1402	0.5557
DOUBLE, TWO DIMENSIONAL	0.1286	0.5392
TRIPLE, THREE DIMENSIONAL	0.1240	0.5276

FRACTION SIGNIFICANT MASS 0.2610  
ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	1214020.7
SIGNIFICANT FIBERS	173700.5
FIBERS > 5UM/TOTAL MASS	40299.4

Table D-16

FIBER TYPE: WOLLASTONITE  
 INDUSTRY: MINING AND MILLING  
 OPERATION: ALL OPERATIONS PCOLED  
 TOTAL FIBERS SIZED 1320  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1596	0.3233
SINGLE CURVED	0.1545	0.3305
DOUBLE, TWO DIMENSIONAL	0.1509	0.3384
TRIPLE, THREE DIMENSIONAL	0.1475	0.3399

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.0697	0.6170
SINGLE, CURVED	0.0695	0.6187
DOUBLE, TWO DIMENSIONAL	0.0626	0.5848
TRIPLE, THREE DIMENSIONAL	0.0598	0.5581

FRACTION SIGNIFICANT FIBERS: 0.1295

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0582	0.6216
SINGLE CURVED	0.0578	0.6229
DOUBLE, TWO DIMENSIONAL	0.0524	0.5881
TRIPLE, THREE DIMENSIONAL	0.0513	0.5599

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0361	0.6442
SINGLE CURVED	0.0360	0.6446
DOUBLE, TWO DIMENSIONAL	0.0314	0.6028
TRIPLE, THREE DIMENSIONAL	0.0303	0.5694

FRACTION SIGNIFICANT MASS 0.7771

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	146614.2
SIGNIFICANT FIBERS	24441.8
FIBERS > 5UM/TOTAL MASS	18993.2

Table D-17

FIBER TYPE: MINEFAL WOOL  
 INDUSTRY: CEILING TILE MFG  
 OPERATION: ALL OPERATIONS POOLED  
 TOTAL FIBERS SIZED 8909  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0340	0.5872
SINGLE CURVED	0.0339	0.5887
DOUBLE, TWO DIMENSIONAL	0.0280	0.5276
TRIPLE, THREE DIMENSIONAL	0.0262	0.4856

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.0520	0.5987
SINGLE, CURVED	0.0519	0.6003
DOUBLE, TWO DIMENSIONAL	0.0436	0.5478
TRIPLE, THREE DIMENSIONAL	0.0405	0.5104

FRACTION SIGNIFICANT FIBERS: 0.2703

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0151	0.4732
SINGLE CURVED	0.0151	0.4760
DOUBLE, TWO DIMENSIONAL	0.0090	0.3771
TRIPLE, THREE DIMENSIONAL	0.0061	0.3182

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0296	0.5305
SINGLE CURVED	0.0294	0.5330
DOUBLE, TWO DIMENSIONAL	0.0220	0.4535
TRIPLE, THREE DIMENSIONAL	0.0190	0.4034

FRACTION SIGNIFICANT MASS 0.0371

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	2090.4
SIGNIFICANT FIBERS	15218.7
FIBERS > 5UM/TOTAL MASS	1894.0

Table D-18

FIBER TYPE: FIBROUS GLASS  
 INDUSTRY: MICRO FIBER PRCD.  
 OPERATION: ALL OPERATIONS FOCLD  
 TOTAL FIBERS SIZED 7906  
 DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1553	0.3032
SINGLE CURVED	0.1500	0.3344
DOUBLE, TWO DIMENSIONAL	0.1308	0.3121
TRIPLE, THREE DIMENSIONAL	0.1177	0.2921

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1568	0.3115
SINGLE, CURVED	0.1522	0.3522
DOUBLE, TWO DIMENSIONAL	0.1252	0.3236
TRIPLE, THREE DIMENSIONAL	0.1091	0.2997

FRACTION SIGNIFICANT FIBERS: 0.6985

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0192	0.4581
SINGLE CURVED	0.0187	0.4690
DOUBLE, TWO DIMENSIONAL	0.0156	0.3575
TRIPLE, THREE DIMENSIONAL	0.0061	0.2834

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0751	0.4160
SINGLE CURVED	0.0718	0.4398
DOUBLE, TWO DIMENSIONAL	0.0517	0.3538
TRIPLE, THREE DIMENSIONAL	0.0388	0.2991

FRACTION SIGNIFICANT MASS 0.1232

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	13233.7
SIGNIFICANT FIBERS	75023.6
FIBERS > 5UM/TOTAL MASS	10147.1

Table D-19

FIBER TYPE: FIBROUS GLASS

INDUSTRY: AIRCRAFT INSULATION

OPERATION: ALL OPERATIONS POOLED

TOTAL FIBERS SIZED 2498

DEPOSITION, ALL FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.1336	0.3869
SINGLE CURVED	0.1284	0.4035
DOUBLE, TWO DIMENSIONAL	0.1162	0.3759
TRIPLE, THREE DIMENSIONAL	0.1086	0.3551

DEPOSITION, SIGNIFICANT FIBERS BY COUNT

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE, STRAIGHT	0.1469	0.3844
SINGLE, CURVED	0.1414	0.4071
DOUBLE, TWO DIMENSIONAL	0.1244	0.3803
TRIPLE, THREE DIMENSIONAL	0.1148	0.3604

FRACTION SIGNIFICANT FIBERS: 0.6309

DEPOSITION, ALL FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0222	0.5189
SINGLE CURVED	0.0219	0.5231
DOUBLE, TWO DIMENSIONAL	0.0146	0.4304
TRIPLE, THREE DIMENSIONAL	0.0107	0.3721

DEPOSITION, SIGNIFICANT FIBERS BY MASS

FIBER CONFIGURATION	PULMONARY FRACTION	GI FRACTION
SINGLE STRAIGHT	0.0640	0.4873
SINGLE CURVED	0.0615	0.4972
DOUBLE, TWO DIMENSIONAL	0.0475	0.4182
TRIPLE, THREE DIMENSIONAL	0.0392	0.3695

FRACTION SIGNIFICANT MASS 0.1230

ESTIMATED FIBER/MASS RELATIONSHIPS

FRACTION	FIBERS/MICROGRAM
ALL FIBERS	9344.6
SIGNIFICANT FIBERS	47947.0
FIBERS > 5UM/TOTAL MASS	7496.6

APPENDIX E

Photomicrographs of Fiber Types Studied

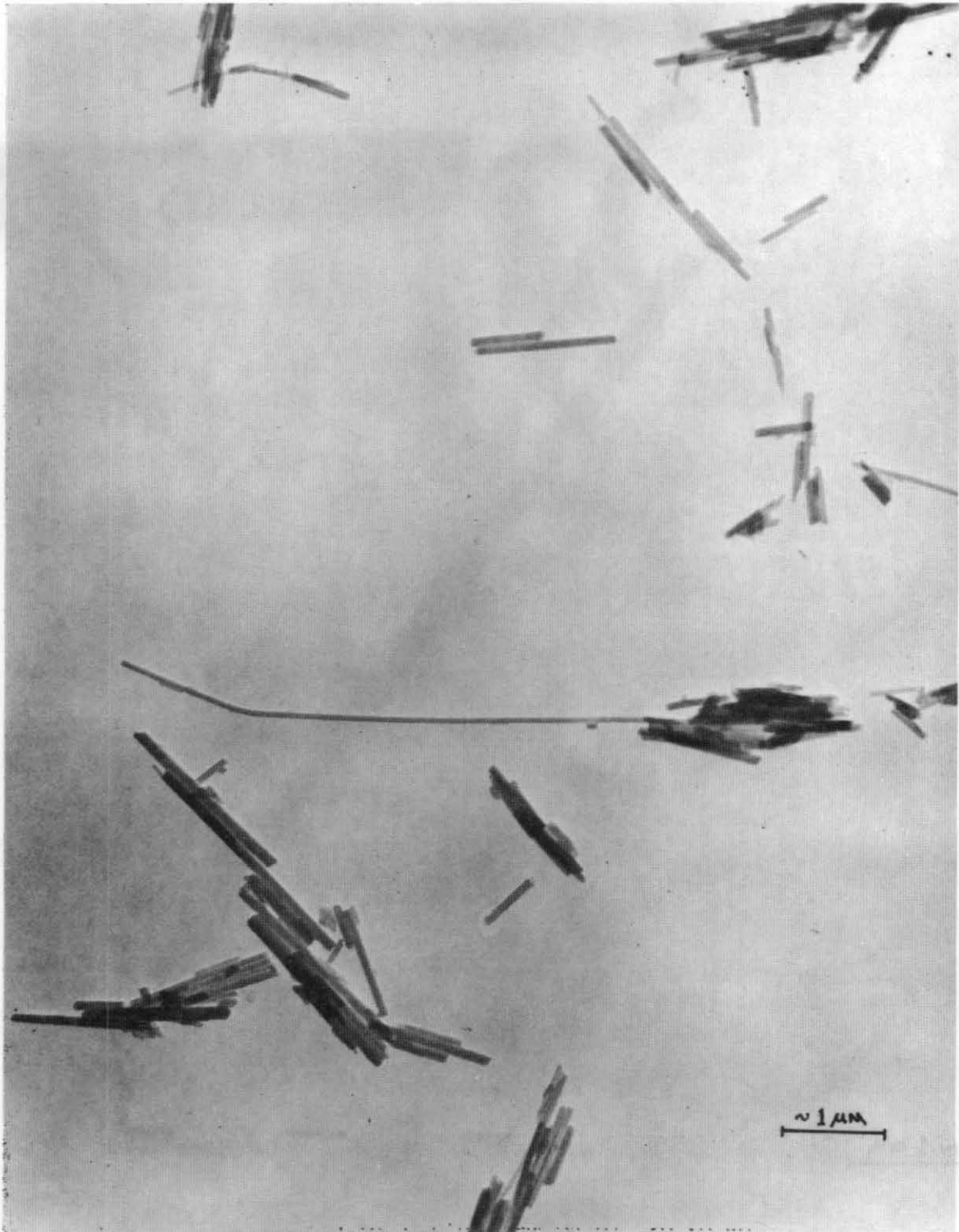


Figure E-1, Chrysotile Asbestos

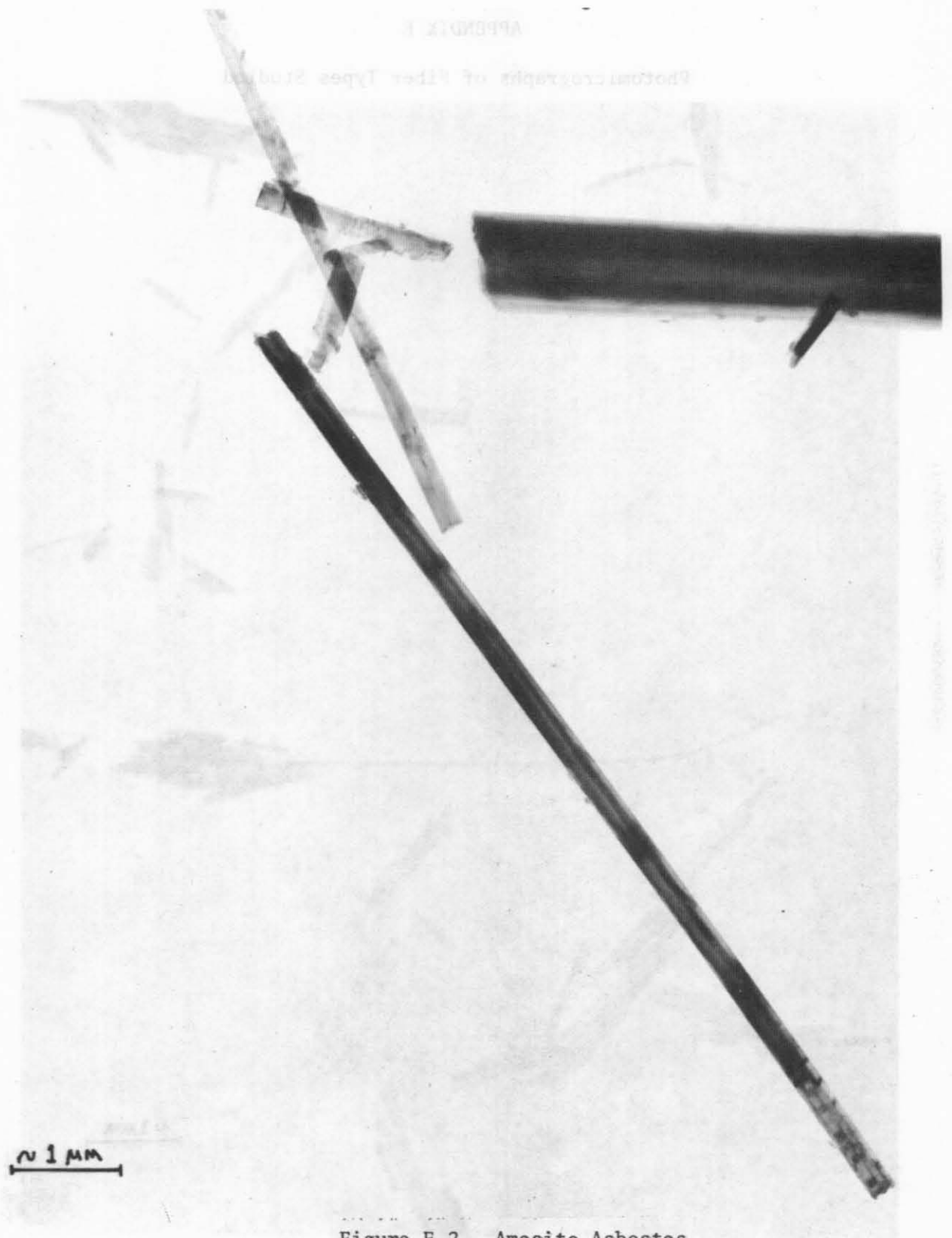


Figure E-2. Amosite Asbestos

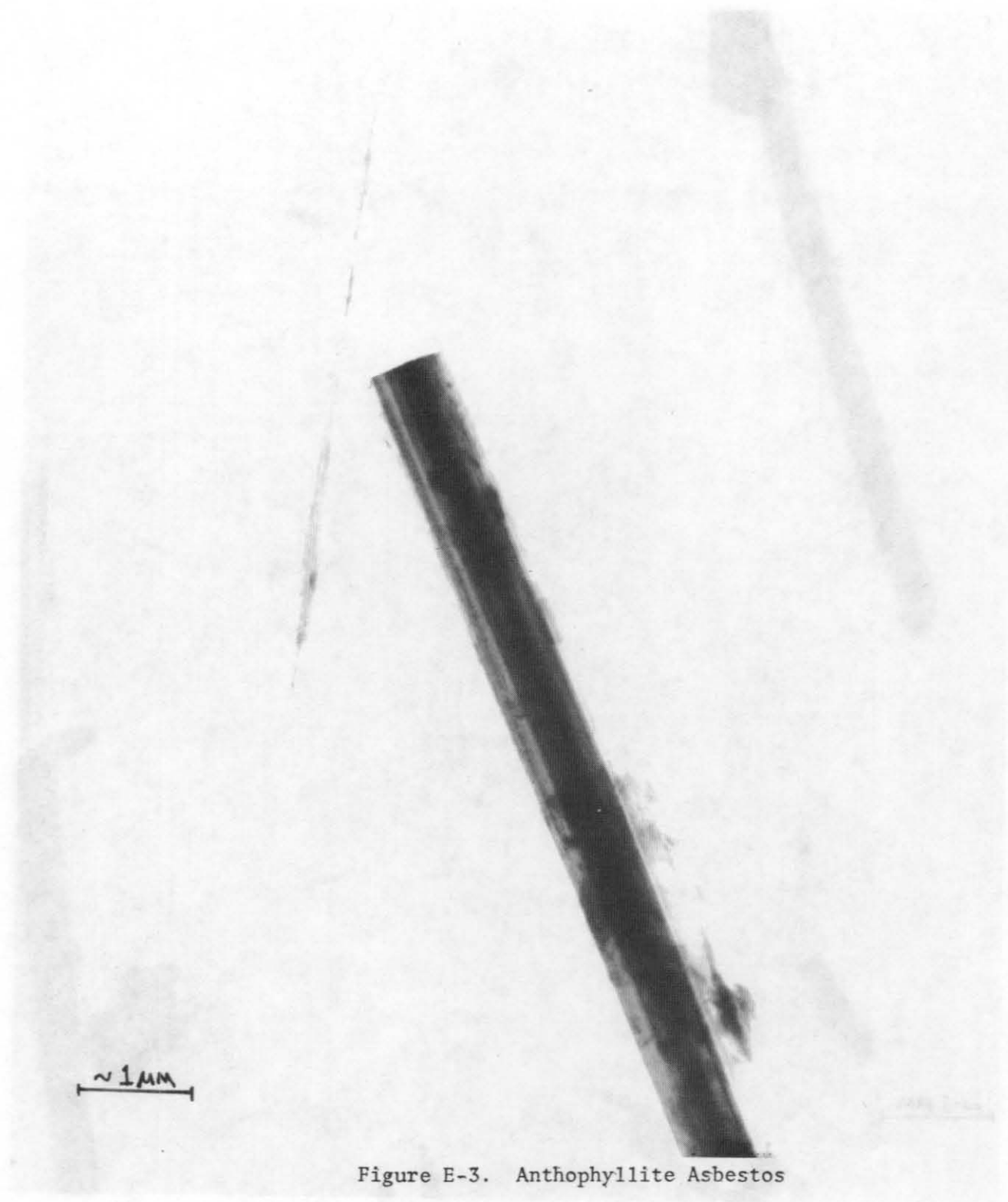


Figure E-3. Anthophyllite Asbestos

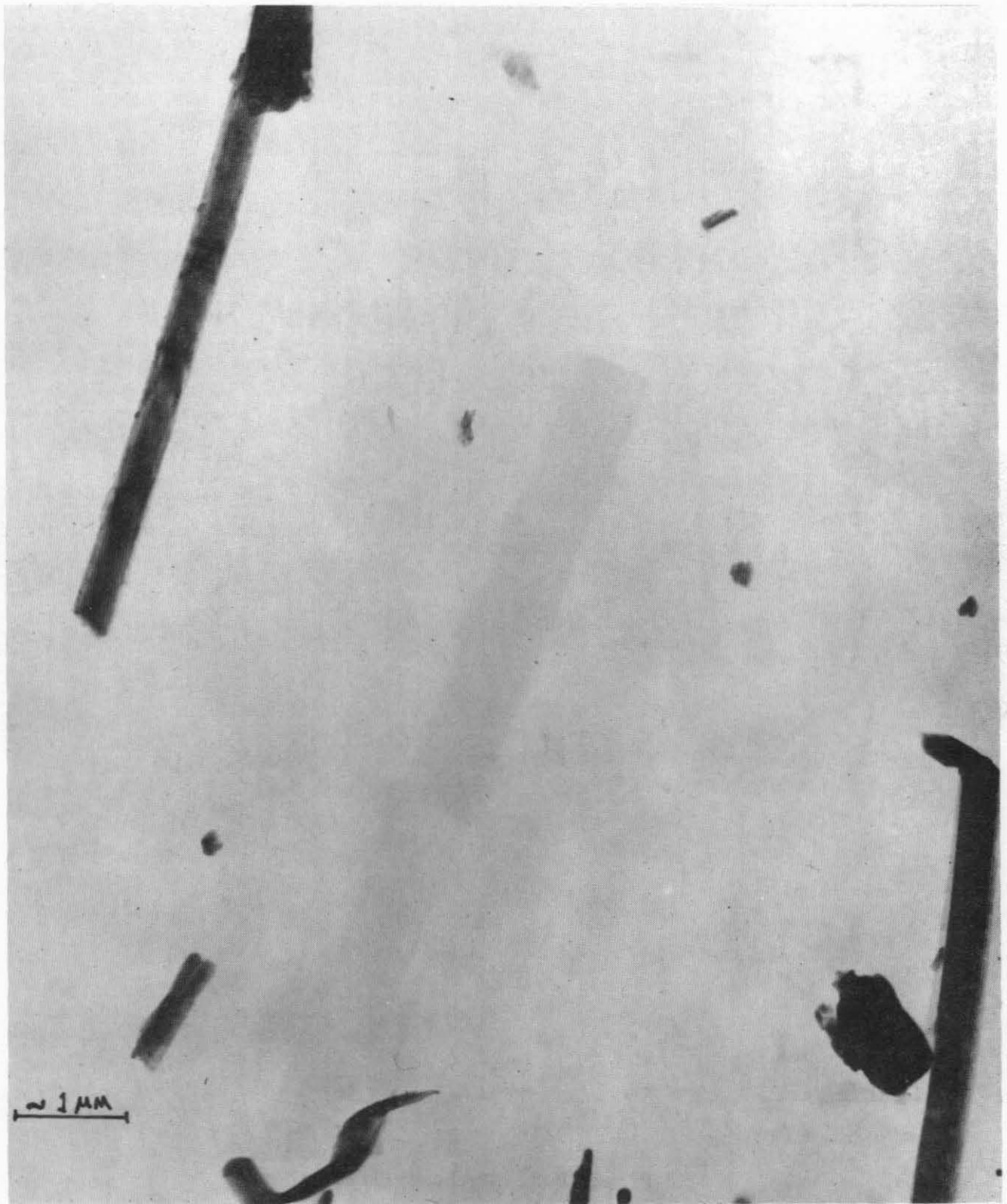


Figure E-4. Tremolite Asbestos

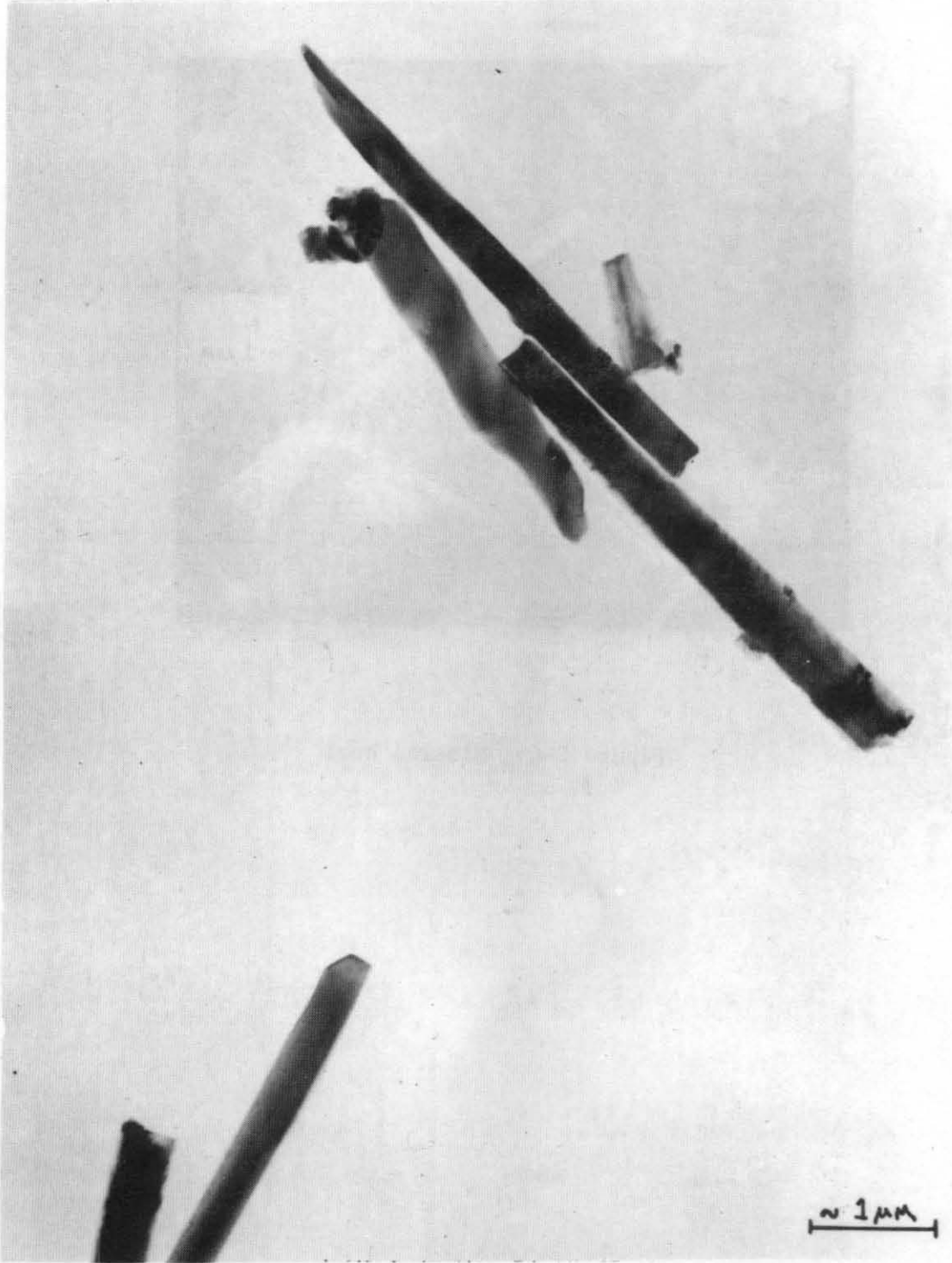


Figure E-5. Wollastonite



Figure E-6. Mineral Wool

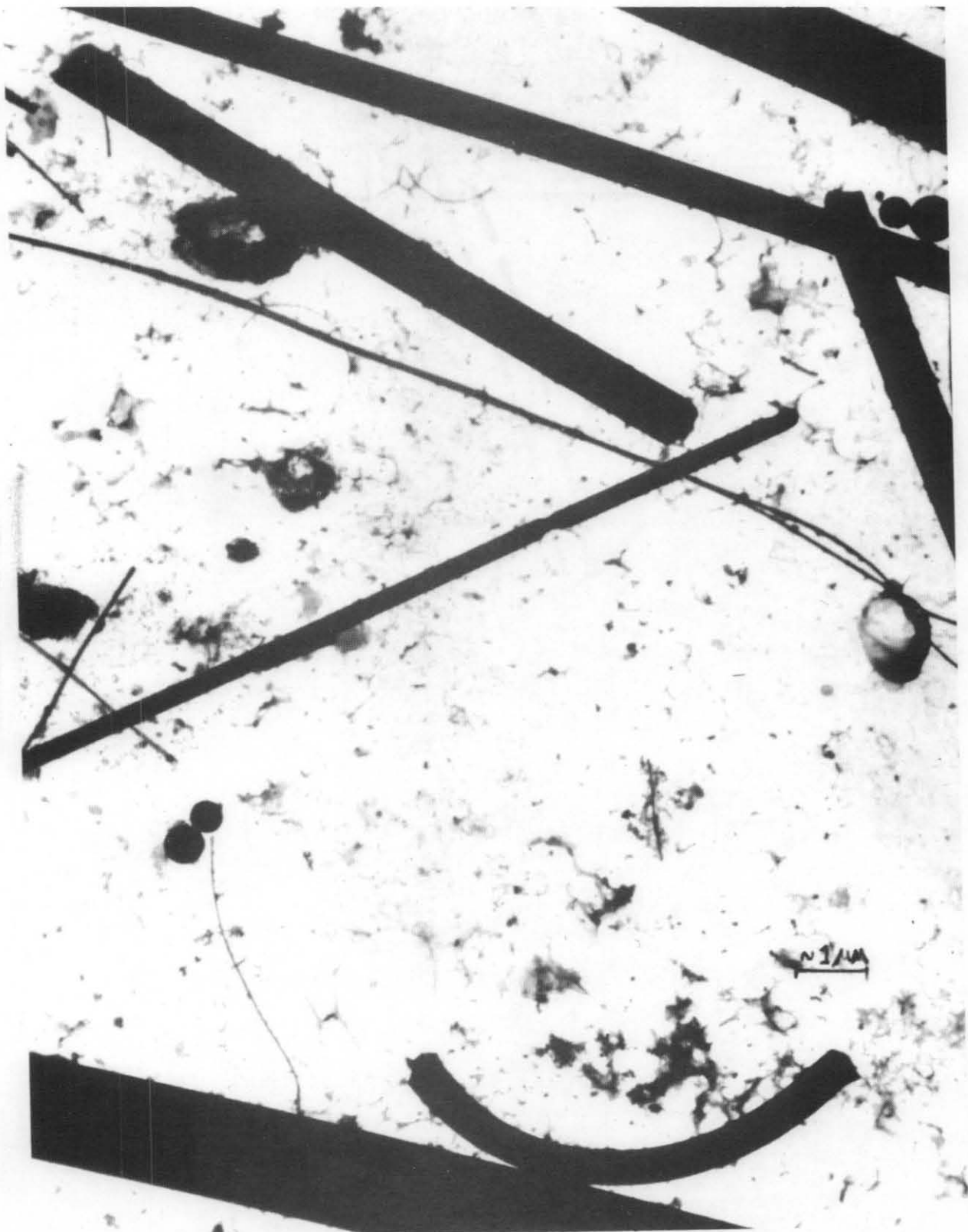


Figure E-7. Fibrous Glass Microfiber